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Development and Assessment of a Decision Support Framework for Enhancing the Forensic Analysis and Interpretation of Fire Patterns

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DEVELOPMENT AND ASSESSMENT OF A DECISION SUPPORT FRAMEWORK FOR ENHANCING THE FORENSIC ANALYSIS AND INTERPRETATION OF FIRE PATTERNS

by

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Abstract

Fire investigators have historically relied upon fire damage to help them make a determination regarding where a fire originated, despite the lack of formal processes for interpreting the reliability of the damage as an appropriate indicator. The historical and current literature on this topic was evaluated. Specific emphasis was given to research related to formation of fire patterns in the context of the fire environment. A seven step reasoning process for identifying, quantifying and evaluating damage in the context of area of origin was then developed, along with a refined definition for the term fire pattern. The reasoning process was then structured as a decision support framework designed to assist forensic fire investigators in assessing the efficacy of fire burn patterns as reliable indicators of the area of fire origin. This was facilitated by the development of a prototype method for determining the area of origin based on fire patterns analysis, named the Process for Origin Determination (POD). The efficacy of the POD was evaluated by two groups of test subjects, one using the POD and one not, using computer-generated images and actual fire scene photographs. This presentation frames the problem, describes the POD, overviews the process used to evaluate the POD, and presents an analysis of the outcomes from the evaluation of the POD, where it is shown through the use of statistical tests of reliability and validity that test subjects who used the POD more consistently and more accurately determined the area of origin over range of test scenarios.

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1.0 Introduction

1.1 Problem Statement

Forensic science is defined as the application of a broad spectrum of sciences to answer questions of interest to the legal system, including both criminal and civil actions (Houck and Siegel 2006). The job of a forensic scientist is to provide scientific evidence, notably the analysis of scientific or engineering data, to the justice system in order to reduce uncertainty (Taroni et al. 2010). Scientific evidence is always incomplete to some degree, which means there is a measure of uncertainty associated within each analysis. Consequently, the forensic scientist must interpret and present the significance of the evidence to the court of law (Taroni et al. 2006).

The investigation of fires is one of the more complicated forensic sciences due to the continuously altered or destroyed evidence by the fire itself. Fire is a highly three-dimensional, time-variant process with time-variant boundary conditions. The other difficulty for forensic scientists investigating fires is that the observations of damage after the fire may often times be independent of the path taken by the fire making it difficult to identify where the fire started. Thus, a fire investigator must have a solid grasp of the physics and variables that influence a fire's development, as well as how these variables may or may not have influenced the damage outcome.

Fire investigation (origin and cause determination) is an integral part of the total fire safety model, including fire prevention and protection for a community. Fire investigation plays a critical role in identifying potentially faulty or improperly designed and installed products that may have played a role in the fire, and in identifying persons that deliberately started a fire with malicious intent.

The scene investigator's most important hypothesis is the correct identification of the origin of the fire (NFPA 2014). The origin determination is necessary to make an accurate cause assessment. Proper fire investigation should determine the fire cause, the cause of the resulting property damage, and most importantly, the cause of bodily injury or loss of life to civilians and firefighters.

Since the beginning of organized fire investigation in the late 1940's, fire investigators have relied on fire patterns as their basis for determining the fire origin (Rethoret 1945). Fire patterns are defined as the "visible or measurable physical changes, or identifiable shapes, formed by a fire effect or group of fire effects" (NFPA 2014). Absent the testimony of reliable eyewitnesses to or recording of the fire's inception, the investigator is required to determine the origin by observation and expert interpretation of the physical evidence (e.g. fire patterns) in an attempt to reconstruct the fire's development. As such, fire origin determination is largely a matter of fire pattern recognition and interpretation (NFPA 2014).

Presently, much of this interpretation is implicit and subject to investigator bias, with assignment of interpretation to patterns being largely dependent on the investigator's knowledge, experience, education, training, and skill, without the benefit of a structured framework to help guide the investigator through the process. This is of particular concern with respect to the importance of being able to identify and properly weigh potentially subtle differences from one fire scene to the next, some of which could have significant bearing on the development of the fire and the interpretation of the evidence.

However, not all fire investigators have the same level of education and training, or appreciation for the interaction of the fire in its environment. Historically, fire investigators have been individuals without any formal education or training in scientific methodology. A survey was conducted by the National Center for Forensic Sciences (NCFS) in 2000 where 422 fire investigators revealed that only 33% held a college degree, of which only 10% were related to science or engineering (Minnich 2000). This survey also related that the average fire investigator has only received 60 hours of training, indicating a one-to-two week course. A survey conducted in 2012 reflected similar findings to that of the NCFS survey where 586 fire investigators revealed that 50% had a bachelor's degree or higher, of which only 18% were related to science or engineering (Tinsley and Gorbett 2013). This suggests that many investigators have received the majority of their training through informal on-the-job training. More experienced fire investigators would mentor less experienced fire investigators, unfortunately in some cases, passing on what has since become realized as a collection of myths (NFPA 2014).

The failure in knowledge transfer is most likely because experienced investigators, particularly those who obtained their basic training before 1992, were trained with misinformation and misconceptions (Lentini 2012). A number of those investigators have taken very little additional training since their basic training and, of those, some do not recognize how flawed their early training was or the impact of how the lack of training regarding current techniques influences their conclusions. The most recent example of this failure resulted in the execution of Cameron Todd Willingham by the State of Texas on the basis of an investigation that relied on "poor understandings of fire science and investigators that failed to acknowledge or apply the contemporaneous understanding of the limitations of fire indicators" (Beyler 2009).

The legal and science professions are currently scrutinizing forensic science, which is forcing the nation to question the discipline's scientific foundation (NIJ 2009). Recently, the National Academy of Sciences released a cautionary report regarding analysis that requires expert interpretation of observations (NIJ 2009). In the report, the authors outlined the need to improve the scientific foundations of the forensic disciplines, particularly those that are dependent on qualitative analyses and expert interpretation of observed patterns, including fire investigations (NIJ 2009). One recommendation called for those forensic science disciplines that rely on human interpretation to "adopt procedures and performance standards that guard against bias and error" (NIJ 2009).

The purpose of this dissertation is to develop and implement into practice a decision support framework that assist forensic fire investigators in assessing the efficacy of fire burn patterns as reliable indicators of the area of fire origin.

1.2 Organization of the Dissertation

This dissertation is organized into six chapters as follows:

Chapter 1 (this introduction) provides some background and context of the Ph.D. research.

Chapter 2 served as the basis of a paper that was published in *Fire Science Reviews Journal* (Gorbett et al. 2015a). This chapter presents the results of a review of the literature and research conducted over the past eighty years on the use of damage to determine the area of origin. Key results from this review include the refining of the definition for fire patterns and the distillation of an overall reasoning process for evaluating fire damage into the following seven steps:

(1) Identifying the value in further analysis of a surface or compartment;
(2) Identification of the varying degrees of fire damage (DOFD) along the surfaces of the compartment and contents;
(3) Identifying clusters and trends of damage (fire patterns);
(4) Interpreting the causal factors for the generation of the fire patterns;
(5) Developing area(s) of origin hypotheses;
(6) Testing the hypothetical area(s) of origin; and,
(7) Selecting a final area of origin hypothesis.

Chapter 3 presents a prototype process, named the Process for Origin Determination (POD). The POD is developed through the decomposition of the fundamental questions identified within the overall reasoning process identified in chapter 2.

Chapters 4 and 5 served as the basis of a paper that was submitted to *Fire Technology* (submitted 10 August 2015, with the manuscript number FIRE-D-15-00228), which was under review when this dissertation was published. Chapter 4 outlines the research methodology used to test the POD for determining the area of origin. To test the reliability and validity of this prototype, a survey of novices was used to apply the POD to study-provided scenarios with various areas of origin, heat release rates, and duration. A total of thirty-two scenarios were provided to the participants. Chapter 4 also briefly describes the preparation of information provided to the participants, development and deployment of the data collection tool, and statistical analysis procedures.

Chapter 5 summarizes the main outcomes of this Ph.D. research study (Gorbett et al. 2015b).

Chapter 6 provides discussion regarding the main outcomes of this research study and future areas of research needed.

A total of nine appendices (Appendix A-I) are provided at the end of this document as supplementary material.

Appendix A is a paper titled “Development and Assessment of a Decision Support Framework for Enhancing the Forensic Analysis and Interpretation of Fire Patterns”. This was presented as a plenary paper at the international conference, *International Symposium on Fire Investigations 2010* (Gorbett et al. 2010). This paper addresses the issues with fire investigation and presents a hypothesis to standardize the analysis of fire patterns. The aim is to develop and implement into practice a decision support framework that will assist forensic fire investigators in assessing the efficacy of fire burn patterns as reliable indicators of the area of fire origin. This paper identifies the need for a decision support system, but as this was early in the thought process it did not introduce a functioning prototype.

Appendix B served as the basis of a paper that was published in the Journal of Forensic Science (Gorbett et al. 2014). The development of a degree of fire damage scale for gypsum wallboard, implementation of a new method of characterizing fire damage, and evaluation of the reliability of this new method are discussed. The method was evaluated by comparing degree of fire damage assessments of a novice group with and without the method, and against expert assessments. Thirty-nine “novice” raters assessed damage to a gypsum wallboard surface, completing 66 ratings, first without the method, and then again using the method. The inter-rater reliability was evaluated for ratings of damage without and with the method, and was also compared to an average “expert” rating of damage with the method. Results indicate that the novice raters were more reliable in their analysis of the degree of fire damage to the gypsum surface when using the method, and that when using the method, novices do not rate damage levels significantly differently than the experts.

Appendix C presents a simple example on how to apply the POD as a proof of concept.

Appendix D presents a description of the thirty FDS/SMOKEVIEW simulations that were conducted for testing the POD. Simulations of varying scenarios were completed to evaluate what variables had the greatest influence on the location and magnitude of heat flux within a prescribed compartment fire. The intent of these numerical experiments was to develop varying locations and magnitude of predicted damage for use in testing the POD.

Appendix E provides the background discussion on the development of probabilistic inferences between characteristics of the locations and trends of fire damage in relation to the predominant factors associated with compartment fire dynamics. Bayesian theory, specifically the use of Bayesian Networks (BNs) are discussed here.

Appendx F provides the BN results of each fire pattern generation decision for fire position 1. This appendix serves as a worked example of the BNs.

Appendix G presents the charts for all the reliability and validity tests conducted.

Appendix H provides the FDS simulation code and MATLAB code used within this research study.

Appendix I provides the survey questions used to test the POD.

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2.0 Background and Literature Review

The terminology associated with fire patterns and their use in origin determination has evolved over the past eighty years, so the first task was to identify any separations within the work to better organize the presentation of the literature. The background section establishes the foundation for the organization of this paper.

The earliest texts on fire investigation expressed the importance of using damage and fire patterns in determining the area of origin (Rethoret 1945; Straeter and Crawford 1955; Kennedy 1962; Kirk 1969). Generally, these texts encouraged investigators to visibly identify which side of a content item, wall, or structural member may have been more affected by heat. The varying damage was given many terms by fire investigators and is reflected within the literature, including: fire patterns, burn patterns, indicators, burn indicators, fire fingerprints, fire transfer patterns, and a variety of geometric shapes. Regardless of the terminology used, these fire patterns were used as a means to trace the fire back to the location where it started, the area of origin. Most of the earlier literature supported the idea that specific patterns were indicative of causal links or to the speed of the fire, which was mostly linked to incendiary fires (e.g. pour patterns). Most of these earlier texts, however, do not offer a process on how to use the data, other than vague descriptions on visibly identifying greater areas of damage and tracing fire patterns. Around the late 1970's there was a movement within the profession to describe fire patterns by descriptions of their geometric shapes (e.g. V-pattern, U-pattern, hourglass-pattern). The characteristics associated with the geometric shapes were in some cases linked to the speed of the fire, such as the angle of the V could be interpreted as the fire being fast or slow. These geometric shapes are still currently used within the profession, however, many of the myths associated with their interpretations have fallen into disrepute.

Given the history of using fire patterns within the fire investigation profession, it was reasonable that they would also be included in the first edition (1992), and all subsequent editions of NFPA 921 *Guide for Fire and Explosion Investigations.* NFPA 921 is recognized as establishing the standard of care for the fire investigation profession and is the only consensus document that exists for fire investigators. The importance of fire patterns is clearly reiterated in Section 6.1.1 by stating "the major objective of any fire scene examination is to collect data as required by the scientific method. Such data include the patterns produced by the fire" (NFPA 2014). The chapter on fire patterns underwent reorganization between the 2004-2008 editions to divide fire effects and fire patterns. This was the first time that a distinction was drawn between damage caused by the fire (fire effects) and clusters of fire effects that may have characteristics that assist the fire investigator (fire patterns). Fire effects are the physical or chemical changes that occur to different materials when exposed to the byproducts of combustion (e.g. melting of plastics, oxidation of metals). Fire patterns are identified as the collection of these effects and geometric shapes that these effects produced.

NFPA 921 further lists that fire patterns can be classified by their generation or causal relationship to the fire dynamics by providing the following classes: plume-generated patterns, ventilation-generated patterns, hot gas layer-generated patterns, full-room involvement-generated patterns, and suppression-generated patterns (NFPA 2014).

Assessing the historical and current semantics of the fire investigation literature, the use of fire patterns to determine an area of origin, for purposes of the current paper, can be grouped into four areas of literature that need to be reviewed, including:

(1) Assessing the varying degrees of fire damage (DOFD) along the surfaces of the compartment and contents (i.e. fire effects);
(2) Identifying clusters and trends of damage (i.e. fire patterns);
(3) Interpreting the causal factors for the generation of the fire patterns; and,
(4) Identifying processes of using fire patterns in determining an area of origin.

The objective of this chapter is to review the work that has been done to observe or measure varying damage along compartment and content surfaces, identify fire patterns, identify causal factors for the fire patterns, and apply this information within a process to identify an area of origin, as well as identify gaps and propose new approaches. A literature review was performed in order to achieve the objectives of this study. The literature was received from different databases, primarily ScienceDirect (2012), International Symposium on Fire Investigations conference proceedings, Fire and Arson Investigator-Journal for the International Association of Arson Investigators, and fire investigation textbooks. The following keywords were used for the literature review, including: *fire patterns*, *fire effects*, *fire investigation*, *arson investigation, burn patterns*, and *burn indicators*.

The literature review is limited to structure fire studies. The majority of the experimental work has been conducted in small, residential-sized compartments with one or two ventilation openings. The majority of this review is of North American work. An Excel spreadsheet outlining the variables for all experimental tests reviewed has been developed and also provided.

There are four logical components to the literature review presented:

- The first part of the review describes the work completed for establishing a degree of fire damage assessment for commonly encountered materials in structure fires.
- The second part isolates the work conducted on identifying fire patterns and the characteristics associated with these trends within the damage.
- The third part of the review focuses on the possible causal factors influencing the location and magnitude of damage.
- The fourth part of the review focuses on the practice of using damage in fire investigation to assist in determining the area of fire origin.

2.1 Literature on establishing a degree of fire damage assessment

When a fire develops in an enclosure, the products of combustion (e.g. heat, soot) begin to influence the materials within the compartment. Thus, the lining materials for the walls, ceiling, and floor, as well as the various materials that make up the contents within the compartment, are damaged by this exposure to the products of combustion. The fire investigation community terms the resulting damage as *fire effects*, which are defined as "the observable or measurable changes in or on a material as a result of exposure to the fire" (NFPA 2014).

The degree to which materials are influenced by the developing fire will be a function of the material characteristics, temperature of the products of combustion, and the duration of exposure (NFPA 2014). There are numerous factors that may influence how a material is affected by heat and exposure to incomplete combustion products (e.g. smoke, aerosols). The loss of mass from a material is typically dependent on the material and the exposure to heating. A short list of material properties that may also influence the effects of a material exposed to a fire environment includes: moisture content, thermal conductivity, density, specific heat, critical heat flux, ignition and flame spread propensity, and heat of gasification/vaporization (NFPA 2014).

The damage data used by fire investigators in origin determination starts with the ability of the investigator to observe varying damage along surfaces of contents, walls, ceiling, floor, and structural members. The fire investigator's observations are simply assessing the varying DOFD. Identification of varying DOFD throughout the compartment serves as the basis for interpretation by the investigator. Fire investigation textbooks, guides, and studies describe the use of lines or areas of demarcation in assessing damage. The areas of damage and boundaries of those areas are often referred to as areas and lines of demarcation. Areas of demarcation are locations along a surface that exhibit similar damage characteristics (e.g. magnitude of damage, type of fire effect, color, texture) and are in close proximity to each other. Lines of demarcation are "the borders defining the differences in certain heat and smoke effects of the fire on various materials. They appear between the affected area and adjacent, less-affected areas" (NFPA 2014). Fire investigators are instructed to visually and measurably identify these areas and lines of demarcation.

Ideally, the investigator would be able to look at a material's surface and distinguish the varying DOFD across its surface and this examination would be consistent with the findings of other qualified investigators. However, fire investigators currently use their visual interpretation to give vague descriptions on the varying degrees of damage when reporting their findings. Many fire investigation reports, textbooks, and standards inconsistently report degrees of damage, using a wide range of undefined modifiers, such as greater, lesser, heavy, light, minor, moderate, major, severe, and large, in an attempt to distinguish between levels of damage that they observe and are trying to convey (DeHaan and Icove 2011; Lentini 2012; Madrzykowski and Fleischmann 2012; NFPA 2014; Shanley et al. 1997).

There are a total of 17 fire effects listed in NFPA 921 (2014) that serve as the base list of observations for fire investigators (Table 1). There are hundreds of materials that can be found in residential occupancies, as such there are thousands of studies that would need to be reviewed and summarized here to identify the characteristics of the material properties and the impact that heat has on each material. The focus of this literature review is to identify the work that has been done specifically for forensic applications that have been conducted for identifying ways to observe and characterize varying degrees of fire damage through measurable or visible means. Wood and gypsum wallboard (drywall) were the only materials that had sufficient literature to review in this context.

Table 2-1: Base List of Fire Effects and Observations identified in NFPA 921 (2014)

FIRE EFFECT	OBSERVATION(S)	
	Visible	Measurable
Temperature Estimation	X	
Mass Loss	X	X
Char	X	X
Spalling	X	
Color Changes	X	
Melting of Materials	X	
Thermal Expansion and Deformation	X	X
Oxidation	X	
Deposition	X	
Clean Burn	X	
Calcination	X	X
Window Glass	X	
Furniture Springs	X	
Victim Injuries	X	
Light Bulbs	X	
Rainbow Effect	X	
Enhanced soot deposition-smoke alarms	X	

2.1.1 Wood (Char)

Wood has been and remains a common material used for construction of structures and contents. Therefore, fire investigators within most fire scenes typically find charred material. As such, fire investigators have written about the use of visible and measurable observations related to varying damage to wood for as long as fire investigation has been in existence (Rethoret 1945). However, the visible and measurable observations used in identifying the varying degree of charring have had many misconceptions.

The early texts on fire investigations promoted the use of identifying the varying degree of charring throughout the compartment to assist with origin determination. Rethoret (1945) describes that the fire investigator should "study closely the depth of carbonization at various places, as this will bring the investigator in getting back to the point of origin". Straeter's (1955) text identified that "the point of deepest char in the wood is likely to be the point of origin of the fire". Kennedy (1962) relates that "wooden joists or studding are exposed to burning…the sides exposed to the direction from which the fire is coming will be more severely burned and charred". Prominent forensic scientist, Paul Kirk (1969), wrote in support of using depth of char for fire investigation in the following, "variations in depth of the char will inevitably be noted…and that this feature of the fire is of primary importance". None of these texts, however, provided a methodology to the reader on how to go about identifying what constitutes greater and lesser visible or measurable char damage.

2.1.1.1 Measurable Damage

The use of depth of char and relating this depth to duration of burning has fluctuated as to its usefulness in fire investigations since the mid-1950's. Kirk's (1969) text was the first reference that indicated investigators could use this data for more than just direction of damage when he explained "investigators make measurements with the idea of determining the length of time the fire burned at this point". However, Kirk cautioned that investigators should not place "more than casual emphasis" on placing a direct relation between char depth and time of burning due to the number of variables that could influence the findings and the lack of reliably controlled test data available (Kirk 1969). Despite this warning, several textbooks and journal articles discuss that an investigator can prescribe a 45 minute duration of burning for every 1-inch of char depth (Stickney 1984; Kennedy and Kennedy 1985; Swab 1985). However, others argued that many variables such as the type of wood, variations in burning within the compartment, firefighting operations, and orientation of the wood influenced the rate of charring and suggested that investigators only use the locations of greater depths as relative longer exposures to heating that should not necessarily be tied to a duration of burning (Kirk 1969; DeHaan 1983; Ettling, 1990).

This "rule of thumb" of burning duration had been the source for some misconceptions related to determining if a fire was incendiary and fell into disrepute around the mid-1990's. In the first edition of NFPA 921 (1992) the investigator was cautioned, "that no specific time of burning can be determined based solely upon depth of char". Schroeder later confirmed this assessment by performing a variety of constant heat flux and duration exposure tests on an assortment of wood samples in an attempt to determine if wood could be reliably evaluated by the fire investigator for intensity and duration (Schroeder 1999). Schroeder's results varied widely as to depths of char in relation to the duration and intensity of exposed heat flux, which led him to conclude that wood was not a good indicator for predicting intensity of duration of exposures.

Babrauskas (2005) summarized the research of charring wood and the research behind the use of depth of charring for fire investigators and found that "under conditions of severe, post-flashover room fires, heavy-timber or similar members that have no gaps or joints will char at similar rates to those found in fire-resistance furnace tests – roughly 0.5-0.8 mm/min"…and that "this can be a useful tool in estimating a minimum value for post-flashover burning of the room fire". However, he found "that much higher charring rates apply to floors and to any other wood members where charring is affected by the presence of gaps or joints".

2.1.1.2 Visible Damage

In the early days of fire investigations a common rule among fire investigators was that the visible observation of large shiny blisters of wood char indicated fast fires and that small dull blisters indicated a slower fire, which assisted investigators to conclude that a fire was incendiary or not (Boudreau et al. 1977; Brannigan et al. 1980; Keith and Smith 1984; King 1985; Ettling 1990). The Law Enforcement Assistance Administration (LEAA) documented many of the myths about using the visible appearance of damage to identify arson with the visible appearance of char being one of the predominant misconceptions (Boudreau et al. 1977). Arson investigators were surveyed about how they investigate fires and cited interpretation of "alligatoring" as one of the most common methods of establishing arson. For example, if an investigator observed charred wood with "large, rolling blisters" giving it the appearance of alligator skin, then the fire investigator was to interpret this as a "rapid" fire which was often used then used in concluding that the fire was incendiary in nature. This misconception was so ingrained in the profession that it was repeated as fact in the Fire Investigation Handbook published by the National Bureau of Standards (Brannigan et al. 1980).

The first reference that can be identified related to rejecting this misconception was a discussion by DeHaan (1983). Additional researchers and texts disavowed the use of this visible observation and its connection to the speed of fire (Cooke and Ide 1985; Ettling 1990; NFPA 1992).

Only one article was identified related to the use of visible char appearance in identifying varying DOFD where quantitative measures were attempted (Keith and Smith 1984). This article reiterated the same alligatoring misconception as promulgated at the time, but despite this connection the goal of the article was to establish a method of defining varying DOFD for the visible observation of char (Keith and Smith 1984). In this work, the authors outlined a system that described char as being on a range from 'Number 0 Char' up to 'Number 10 Char', with number 10 char as representing the greatest level of damage. The level of damage was varied based on the visible appearance of the number of cracks within set distances and the widths of those cracks. For example, an investigator would assign a number 5 char level to a piece of wood that had "the number of cracks occurring up to 2 per centimeter with widths approximately the thickness of a five-cent piece" (Keith and Smith 1984). The DOFD as outlined in this article never received any traction within the community and has never been picked up in any other literature.

Figure 2-1: Wood stud wall with varying DOFD char damage

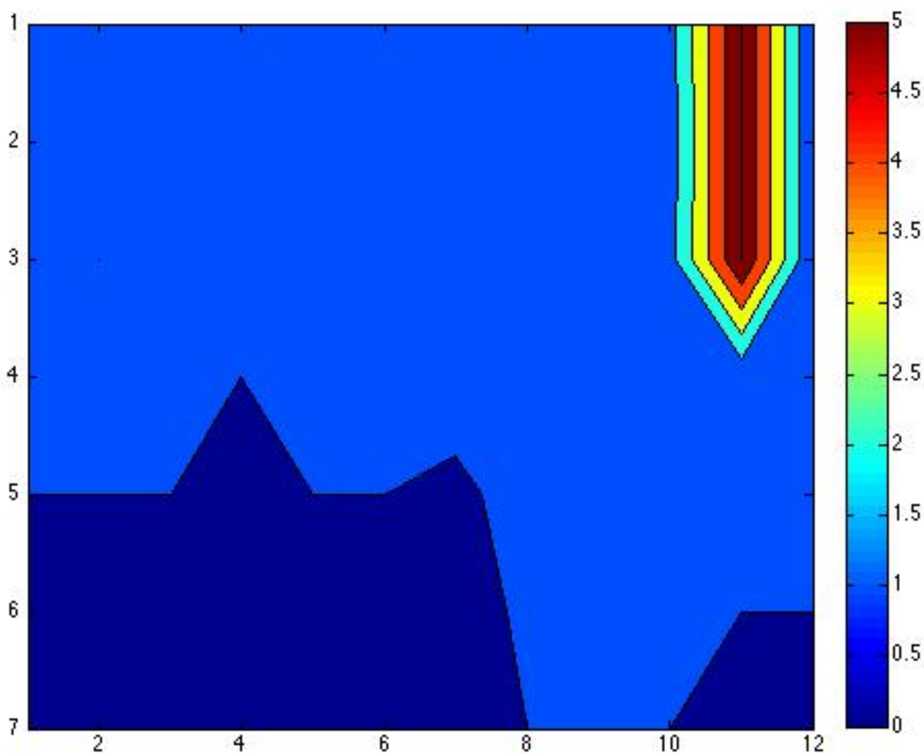

Figure 2-2: Depth of char contour plot of wood stud wall depicted in figure 1.

2.1.2 Gypsum Wallboard / Drywall (Calcination)

Gypsum wallboard is one of the more common lining materials for walls and ceilings used for construction of residential and commercial facilities. Gypsum wallboard is a common structural lining material consisting of a core of gypsum (calcium sulfate dihydrate) sandwiched between two paper facers (McGraw and Mowrer 1999).

There are several effects that may occur to gypsum wallboard when exposed to heat and fire conditions, including: color changes, soot deposition, charred paper, paper consumed, and clean burn (Figure 4). Determining which effect or effects reflect varying degrees of damage is the key to successfully assessing damage. Two methods are used to visibly interpret damage on gypsum wallboard (1) cross-sections of the wall can be evaluated for visibly identifiable changes to the gypsum wallboard through depth, and (2) the surface effects can be evaluated for visibly identifiable varying DOFD.

Much of the earlier published research was focused on examining cross-sections of the wallboard, visibly determining the depth of calcination based on different bands of color within the cross-section (Posey and Posey 1983). The Posey study reported that an investigator could visibly identify subtle color changes in individually cut cross-sections of the wallboard and prescribe the DOFD associated with the color changes. Several researchers supported this analysis but questioned the practical application of such a method (Schroeder 1999; Kennedy et al. 2003). Other researchers have shown that the cross-sectioning method is misleading, as well as having significant procedural drawbacks (Mann and Putaansuu 2010; Mealy and Gottuk 2012). Most recent studies consider taking the actual depth of calcination by using an instrument and probing it into the wall a more effective method (Mann and Putaansuu, 2010; Mealy and Gottuk, 2012; Kennedy et al. 2003). Therefore, the visual identification of color changes through the cross-sectioning of wallboard will not be further addressed.

2.1.2.1 Measurable Damage

The first reference that fire investigators were able to use depth of calcination for origin determination can be found in 1955, where the authors of this text relate depth of char methods to that which can also be done to "spoiled plaster (drywall) or concrete may indicate the point of origin by a similar means of determining greatest damage" (Straeter and Crawford 1955). The Schroeder study (1999), however, was the first to quantify the depth of calcination and its relationship within fire investigations. In this study, experimental samples of gypsum wallboard were exposed to various heat fluxes at varying durations using the ASTM E1354, Cone Calorimeter radiant heater. Schroeder was able to illustrate that a crystalline change would occur within the gypsum wallboard when heated by using an x-ray diffraction technique. His findings indicate that gypsum wallboard was the only material that could be reliably used for predicting intensity and duration purposes. However, Schroeder's study did not produce an effective means for implementing this method into a scene inspection.

Ngu (2004) performed similar experimental work as Schroder (1999). In the Ngu study, a series of power law correlation plots were developed between the calcination of gypsum wallboard and the total heat exposure for various types and thicknesses of the material (2004). From this work, Ngu developed a tool based on a constant spring force and a force probe. Ngu performed simple bench top tests to evaluate this tool's ability to reliably obtain depth measurements. Ngu did not test this methodology for application toward full-scale fires for investigation purposes.

Mealy, Wolfe, and Gottuk (2013) designed a tool based on the previous work of Ngu (2004), which used a force gauge with an attached hex key probe (2mm diameter). The Mealy, Wolfe, and Gottuk study used the Ngu force gauge to ensure that the user performed their measurements with similar force (Mealy et al. 2013). They confirmed that 6.6lbf (3 kgf) of force was best at matching the Fourier Transform Infrared spectroscopy (FTIR) chemical analysis of dehydration found in the Mann and Putaansuu study (2010). The Mealy study (2013) indicated that a variance on the depth measurements, regardless of the user, was negligible (~10% variance) and that the method worked at reliably indicating fire travel, especially when no visible observations could be made. The Mealy, et al. study (2013) also demonstrated that when visual damage to the wall surfaces were unable to provide enough data for analysis that contour plots of the depth measurements "provided valuable insight into the areas within the enclosure that were subjected to the most severe thermal damage, the areas in which the initiating (primary first fuel) fire occurred". This quote, however, is not to generalize that the area of origin is to be equated with the area of greatest thermal damage outside of this specific test series.

Although these studies demonstrated that depth of calcination surveys assisted in the area of origin determination, neither developed a process to quickly process a fire scene. The prescribed process by Mealy (2013) was time consuming due to the requirement on the user to be extremely careful in watching the gauge and then marking the probe with a piece of tape to document the depth, thus introducing potential error.

Barnott, Hardman, and Hoff (2013) developed a constant force depth of calcination tool to eliminate inconsistencies in depth of calcination measurements to provide a more practical application of the tool based on the Ngu (2004) and Mealy (2013) studies. The tool used constant force springs to ensure an even, consistent pressure is applied at all times regardless of the user. The tool is built around a digital indicator gauge commonly used in machining. The gauge is capable of reading measurements to 0.0005" (0.01 mm).

The constant force is applied to the tool by two 3.3 pound constant force springs. The use of 2 springs running parallel to each other allows for equal pressure on each side of the tool (Figure 3). The measuring pin is constructed of a 2mm cobalt drill bit. The pin size was based on the Mealy (2013) research, which resulted in a pressure of 1175psi (0.86 kg/mm^2). Resistance in the tool system is minimized through the use of UHMW-PE TIVAR plastic on all sliding surfaces, eliminating metal on metal contact. This includes the spring housing and rear slider block. This study also developed a simplified grid system out of tent pole stakes to decrease scene processing time.

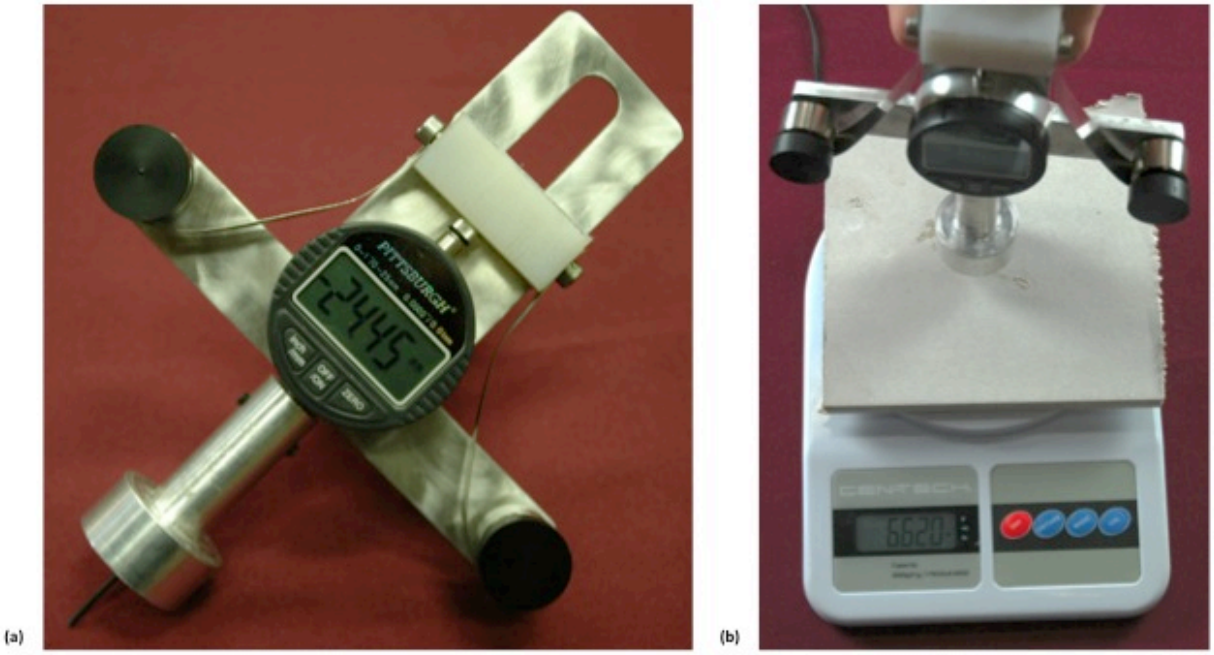

Figure 2-3: (a) Depth of Calcination Tool Developed for Constant Pressure Measurement, (b) 6.6lbf (3 kgf) Confirmation (Barnott et al. 2013)

2.1.2.2 Visible Damage

Most investigators in the field do not cut out pieces of the wallboard to visibly identify damage, nor do they perform depth surveys using a depth tool. Typically, investigators look at the face of the wallboard and make a visible determination of the DOFD. The visible appearance of wallboard has been utilized in all fire pattern studies available, even though only a few studies exist that focus on the baseline characteristics of the varying degree of heating and resulting DOFD (Madrzykowski and Fleischmann 2012; Hicks et al. 2008; Mann and Putaansuu 2009). Therefore, no systematic scale for the degree of damage had been proposed or adopted. NFPA 921 (NFPA 2014) provides some generic guidance regarding the changes in visible appearance to gypsum wallboard in response to heating, but no formal scale had been proposed.

Hicks et al. (2006; 2008) conducted a fire pattern reproducibility study using single fuel items. Forty-eight tests were conducted with a standardized ANSI/UL wood crib and ten additional tests were conducted with commercially available polyurethane foam recliners. The fuels were burned against a gypsum wallboard lining material within a compartment lined with gypsum wallboard. Twelve thermocouples were mounted in a grid array above the fuel item to capture temperatures for the duration of the tests. These two studies demonstrated a relatively predictable response of visible damage to the gypsum wallboard consistent with the varying DOFD identified in NFPA 921 (Figures 4-5).

Figure 2-4: Varying Degree of Fire Damage to Gypsum Wallboard-Visible Damage Results.

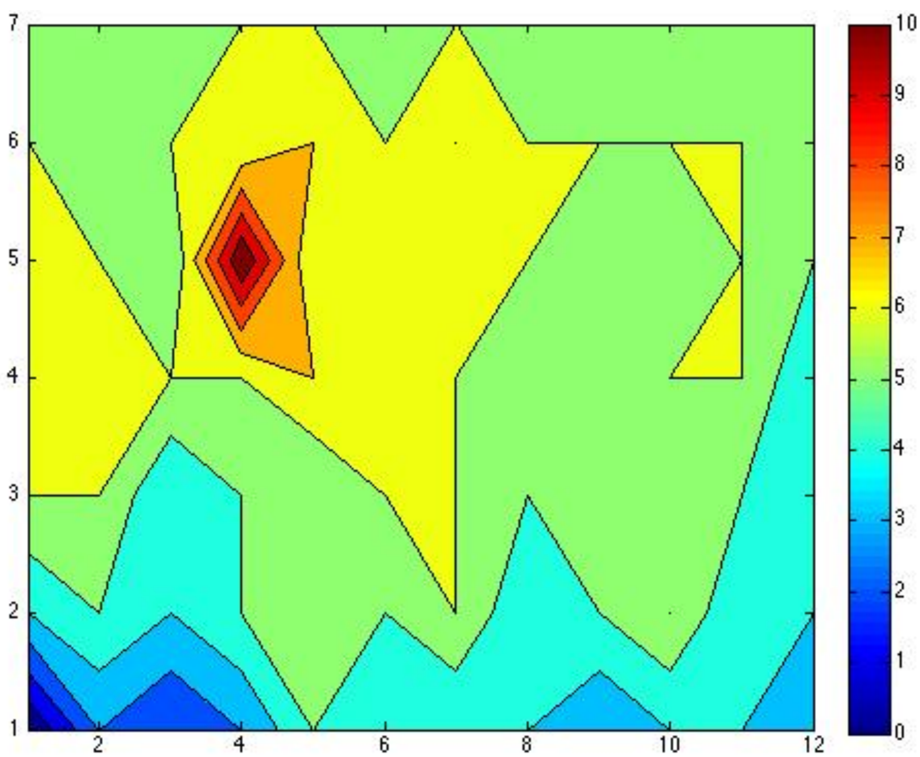

Figure 2-5: Varying Degree of Fire Damage to Gypsum Wallboard-Contour Plot of the Depth of Calcination Results of Figure 4.

Madrzykowski and Fleischmann (2012) performed a study of the response of gypsum wallboard and the reproducibility of the damage pattern created when exposed to known heat release rate (HRR) fires with varying types of fuel sources and wall construction. The fuels used for their experiments included a natural gas burner, gasoline pool fire, and polyurethane foam. The wall construction was varied between a single sheet of gypsum wallboard with wood framing, a gypsum wallboard front and back with wood framing, and gypsum wallboard front and back with fiberglass batt insulation in the voids of the wood framing. The gypsum wallboard was covered with a primer and cover coats of latex paint. This study focused on the effects where the paper had been burned away (consumed) and where the paper had been peeled up (penetration). To accomplish this, the researchers evaluated the variability of the flame height in comparison to the height and area of damage. As expected, the results indicated that the patterns generated by the polyurethane foam fire had greater uncertainty than the natural gas and gasoline pool fires. The wall construction had no significant impact on the damage.

Mann and Putaansuu (2010) exposed samples of gypsum wallboard to three levels of heat flux for three different durations and noted visible changes, as well as depth of calcination changes with a variety of probing instruments. Their study reported that the fire damage to the surface and internal cross section of the wallboard occurs progressively in the following manner:

1. Soot coating of undamaged facing paper;
2. Discoloration / degradation of facing paper;
3. Facing paper burns away;
4. Partial dehydration and discoloration / soot staining of surface layer of gypsum;
5. Formation of anhydrous and hemihydrate layers with layers progressing through the cross section;
6. Complete conversion of dihydrate to anhydrous and hemihydrate;
7. Anhydrous extends through the entire cross section;
8. Wallboard becomes catastrophically heat damaged and lacks structural integrity.

Mealy, Wolfe, and Gottuk (2013) also discuss findings related to the visual identification of surface damage progression to gypsum wallboard based on imposed heat fluxes. They further confirmed the NFPA 921's and Mann and Putaansuu's progressive visible damage to the surface of the gypsum wallboard.

Riahi studied the soot deposition characteristics of three different fuels in bench-scale experiments and then against a gypsum wallboard lined wall (Riahi and Beyler 2011; Riahi 2012; Riahi et al. 2013). An optical measurement method was developed to arrive at optical properties of smoke deposited out of a smoke layer onto glass filters. From this work, the researchers used gravimetric measurements of these filters to demonstrate and validate an analytical model for smoke deposition based on thermophoresis. Consequently, a new optical measurement method was developed to use with digital photographs and digital image analysis. The researchers used ImageJ software and a Kodak gray scale and found good agreement between the optical measurement methods and smoke pattern images developed along wall surfaces. Their study showed that "the smoke pattern was determined for the wall tests and showed a difference between test conditions and very good agreement for the method for all test conditions" (Riahi 2012). They also stated that "based on the clean zone area, the flame height and the fire size can be calculated" (Riahi 2012). Finally, the study was conducted with a variety of digital cameras, and they found that the optical properties were not dependent on the camera used.

The varying DOFD discussed in NFPA 921 is consistent with the findings from the existing studies (Schroeder 1999; Hicks 2006; Hicks 2008; Mann and Putaansuu 2010; Madrzykowski 2012; Mealy et al. 2013). A DOFD scale for gypsum wallboard was developed and tested based on the findings from these studies (Gorbett et al. 2014). In this study, a DOFD scale was developed as a ranking system to reflect the varying degrees of visible fire damage to gypsum wallboard based on its response to heat exposure and visible damage indicators. A scale ranging from 0 to 6 was developed for assigning a DOFD, with 0 indicating no visible damage and 6 indicating complete consumption. Thirty-nine "novice" raters performed an analysis of damage to a wall surface, completing 66 ratings first without the DOFD method and second, repeated rating with the new DOFD method. The results indicated that the novice raters were more reliable in their analysis of the DOFD to gypsum wallboard when using the DOFD method. These results support the use of standardized processes to decrease the variability in data collection and interpretation.

2.2 Literature on Identifying Fire Patterns

As one early fire investigation text declares, "patterns are the cornerstone of all fire investigation because of their universal applicability" (DeHaan 1983). It is important to evaluate the evolution of the term *fire pattern* to better evaluate what literature exists.

Fire pattern was first used to describe how the fire developed or had traveled as described by Kirk, "every fire forms a pattern that is determined chiefly by the configuration of the environment and the availability of combustible material" (Kirk 1969). The term or similar terms were later defined in subsequent texts as "where the fire's destruction took place and where it did not" (DeHaan 1983). In the United Kingdom the use of fire patterns can be found within the literature, though, they tended to discuss these as *directional signposts* where the "heat flow will cause asymmetric effects within the building" (Cooke and Ide 1985). These early definitions are broad and all encompassing of the entire fire scene. The first attempt at consolidating patterns was the first edition of NFPA 921, however many misconceptions had spawned up between the early 1960's and the publication of NFPA 921 (NFPA 1992).

The Law Enforcement Assistance Administration (LEAA) documented many of the myths about using the visible appearance of damage to identify arson (Boudreau et al. 1977). Arson investigators were surveyed about how they investigate fires and cited interpretation of "burn indicators" as the most common method of establishing arson. Some of these indicators used were alligatoring, crazing of glass, depth of char, lines of demarcation, sagged furniture springs and spalled concrete. The LEAA report, after listing the indicators, identified that these indicators have received little or no scientific testing and that "there appears to be no published material in the scientific literature to substantiate their validity" (Boudreau et al. 1977). Despite the lack of validity and this caution, the training and textbooks within the profession during this time used these indicators as a means to link an observation to the speed of the fire and ultimately to the conclusion of fire cause.

In 1992, NFPA 921's first edition identified most of these old indicators as misconceptions. This first edition was also the first time fire patterns were organized into one document. NFPA 921's original definition stated "fire patterns are the physical effects that are visible or measurable remaining after a fire…including thermal effects on materials, such as charring, oxidation, consumption of combustibles, smoke and soot deposits, distortion, melting, color changes, changes in the character of materials, structural collapse, and other effects" (NFPA 1992).

The original definition of fire patterns and how it was used in NFPA 921 was all inclusive of the varying degree of damage to materials, clusters of damage, geometric shapes, and the process of using damage to arrive at an area of origin. It was not until 2008 that NFPA 921 changed the definition of the term with the introduction of the term *fire effects*. The definition of fire patterns evolved to "the visible or measurable physical changes, or identifiable shapes, formed by a fire effect or group of fire effects" (NFPA 2008). The definition of fire effects became "observable or measurable changes in or on a material as the result of a fire" (NFPA 2008). Fire effects are the bases for the varying DOFD that was discussed in the previous section. This did not so much redefine the NFPA 921 coverage of the topic, but rather clarified the fire investigator's interpretation process in identifying a fire pattern.

The evolution in terminology clarifies how *fire patterns* became a more restricted definition, and it is this bounded term that will be the focus of this literature review section. Prior to discussing the patterns themselves and their historical progression, it is first important to recognize that lines of demarcation or areas of demarcation serve as the borders of a fire pattern and should be defined. Areas of demarcation are locations along a surface that exhibit similar damage characteristics (e.g. magnitude of damage, type of fire effect, color, texture) and are in close proximity to each other. Lines of demarcation are "the borders defining the differences in certain heat and smoke effects of the fire on various materials. They appear between the affected area and adjacent, less-affected areas" (NFPA 2014).

The fire testing conducted for fire patterns has evolved with the changing definition of the term. As such, a subsection on testing is first presented to describe all fire pattern tests conducted, not just those evaluating the current use of the term. The tests were typically conducted to evaluate multiple aspects of using damage for origin determination and not just within the context of clusters of damage, therefore, many of these tests will describe fire effects, clusters of fire effects, fire pattern generation, and the use of fire patterns to arrive at an area of origin. The tests will be summarized chronologically in this section and will be referred to in other sections of the literature review where the work specifically addresses that subject matter.

2.2.1 Fire Tests Conducted Related to Fire Patterns

All of the fire pattern studies have been summarized in an excel spreadsheet. This spreadsheet provides all of the test details, general instrumentation results, list of indicators identified or not, and provides the probability for the identification of these indicators.

The first published fire pattern tests was in 1984 (Custer and Wright 1984). Two 15 feet by 15 feet (4.57m x 4.57m) structures with a ceiling height of 7 feet (2.13m) were tested. The compartments were of frame construction with unfinished wood lining the interior of the compartment. There were two windows and one door, where one window was closed and the other open for the fire duration, while the door was opened 5 minutes post-ignition. The open window was 3 feet by 3 feet (0.91m x 0.91m) with a sill of 2 feet (0.61m) that was directly across the room from the doorway that was 3 feet by 6 feet (0.91m x 1.83m). Both compartments were furnished similarly with a sofa located under the open window, a sofa located along the wall next to the door, and a kitchen table in the center of the compartment.

The origin of both fires was located under the window in the sofa, but different accelerants were used to start each test fire with 2-gallons of gasoline in test 1 and scattered newspaper in test 2. A thermocouple tree was located at the area of origin. Each test fire was conducted for 10 minutes, with the door opened at 5 minutes. The researchers report negligible winds on the day of the tests. Both tests resulted in an area of greatest damage directly across the room from the window opening, the opposite side of the room from the true origin.

This test was conducted as part of a conference where the participants of the conference were to evaluate the fire scenes for origin. It was reported, "many of the investigators had difficulty finding the location of the point of origin, in many cases indicating the opposite side of the room" (Custer and Wright 1984). The conclusion reached by the researchers was that "it would appear that the major conclusion which can be drawn from this study is that ventilation conditions in the early stages of a fire can cause an anomalous fire spread, thus giving a false impression as to the point of origin" (Custer and Wright 1984). The researchers consequently provide guidance to investigators on how to resolve this situation by saying "it is necessary to pay particular attention to low burns and shadow effects on room furnishings" (Custer and Wright 1984).

In 1997 The United States Fire Administration (USFA), in conjunction with the National Institute of Standards and Technology, Building and Fire Research Laboratory (NIST-BFRL) launched the fire pattern research committee and produced the USFA Fire Pattern Test report (Shanley et al. 1997). This project consisted of 10 separate full-scale tests to produce the first scientifically controlled and recorded research into the formation, growth, and investigation of patterns produced in fires. These tests produced the first published data that supported fire patterns as being useful in fire investigation. However, this report also demonstrated that in two tests, "distinctive patterns were produced which without careful study and a full understanding of all factors which influenced the progress and growth of the fire, could easily be interpreted to indicate incorrect or multiple origins" (Shanley et al. 1997).

This study noted that flashover and ventilation was one of the most misunderstood variables, having the influence to alter "normal" fire pattern production. Most notably, "patterns which indicated areas of intense burning but were remote from the point of origin were observed and were determined to be from ventilation effects only. This was observed in rooms, which had flashover conditions where clean burn areas were produced under windows away from the origin. This was also observed on walls opposite door openings" (Shanley et al. 1997). Heat and flame vector analysis was used as a process within these studies to document the direction of fire travel, location, and magnitude of fire patterns, as well as a process of confirming the area of origin. Again, no procedural details were provided on how to implement the heat and flame vector analysis, but this was the first time that formalized diagrams and legends were published as demonstrative aids.

In March of 1997 four full-size compartment test fires were conducted in furnished bedrooms (Milke and Hill 1997). The compartments were 12 feet by 12 feet with 8 feet ceiling heights (3.6m x 3.6m x 2.4m) with a single door opening 3 feet by 6 ft-10 inches (0.91m x 2.1m). The rooms were instrumented with heat flux gauges, thermocouples, and gas sampling probes. The burns were intended to be identical to determine if differences would be discovered with a close analysis of the results. In all cases, ignition of a gasoline spill next to an upholstered chair was used to initiate the fire. The researchers noted differences, and attributed these to small variations in the inflow of air.

Another series of full-scale fire tests was conducted with funding provided by the National Institute of Justice (Putorti 1997). Putorti reported, "comparisons of the conditions of the rooms and furnishings after the experiments resulted in the determination of several similarities, as well as many differences, between experiments with the same method of ignition" (Putorti 1997). He attributes the differences to the "ventilation effects."

In 2003, ten full-scale test burns were performed in a ISO 9705 room 12 feet by 12 feet with 8 feet ceiling heights (3.6m x 3.6m x 2.4m) with a primary focus on examining television sets and electronic appliances exposed to a full-scale room fire (Hoffmann et al. 2003). Six tests were completed with television sets placed inside a wood entertainment center. Two tests were completed with television sets placed on a wood stand next to an upholstered chair. These eight tests were "allowed to continue until just before flashover conditions were attained" (Hoffmann et al. 2003).

The ignition varied where four tests had a 2 feet (0.61m) diameter pan of Isopropyl Alcohol (IPA) used to ignite a small electrical appliance adjacent to the television set, two tests were ignited by applying the IPA fueled fire directly to the television set, and the last two non-full room involvement tests were ignited with the use of newspaper sheets under the cushion and on the floor in front of the upholstered chair. The final two tests were performed after "multiple television sets and electronic appliances were placed on wood stands and on the floor in a burn room containing an upholstered chair and area rug…both of these tests were allowed to progress into full-room involvement and were not extinguished until four minutes past flashover" (Hoffmann et al. 2003).

The researchers stated that one of the objectives of their tests "was to determine if burn patterns in the room were consistent with the origin or location of the external fire" (Hoffmann et al. 2003). The results for the eight tests that did not reach full-room involvement were reported as having "asymmetric fire patterns and heat damage was consistent with the location of the exposure fire for all but one pre-flashover exposure fire test" (Hoffmann et al. 2003). The one test that deviated showed a V-pattern emanating from the floor behind the entertainment center giving the appearance that the "fire origin could be interpreted to be located on or near the floor behind the entertainment center when the fire origin was to the left and along side the television inside the entertainment center" (Hoffmann et al. 2003). The researchers report this deviation in the fire patterns was caused by "the burning, melting and dripping of the plastic electronic appliance next to the television" (Hoffmann et al. 2003).

The two tests that resulted in full-room involvement showed that "burn patterns could be generated which were not indicative of the area of origin of the fire" (Hoffmann et al. 2003). In one of these tests it was found that "other burn patterns in the flashover tests showed similar misleading patterns from asymmetric burning of a television set, with the most damage on the side away from the origin of the fire to patterns on the gypsum walls indicating a V-pattern pointing to a television stand and associated electronics" (Hoffmann et al. 2003). The room burns produced patterns that were both consistent with the origin as well as burn patterns and V-patterns that were inconsistent with the origin.

Beginning in March of 2005, a series of twenty full-scale fire pattern tests were conducted at Eastern Kentucky University (Gorbett et al. 2006; Hopkins et al. 2007; Hopkins et al. 2008; Hopkins et al. 2009; Gorbett et al. 2010; Gorbett et al. 2013). The test fires were conducted in identically constructed, finished, and furnished living room and bedroom compartments within a burn building. These studies focused on fire pattern reproducibility, pattern persistence through flashover, the use of fire patterns in origin determination, and the influence of initial, low HRR fuel on fire pattern production. The researchers discuss that similar truncated cone patterns were identified in the first eight tests (Gorbett et al. 2006). The most important finding from these tests is that "the interpretation of *all* fire effects provides substantial evidence for the investigator to identify the correct area of origin" (Gorbett et al. 2010). These studies contended that the use of the heat and flame vector analysis enabled the investigator to determine the true area of origin. Fire effects were listed for each test, fire patterns identified, and formal heat and flame vector analysis legends and diagrams were provided for each test. However, no procedural details were provided on how to implement the analysis.

In 2005 and 2008, three studies were completed in conjunction with a training seminar to analyze burn pattern development in post-flashover fires (Carman 2008). This study focused on the impact of ventilation on fire patterns and the ability of fire investigators to use fire patterns to determine the quadrant of the room where the fire began. The test was conducted in a single compartment measuring 14 feet by 12 feet by 8 feet high (4.26m x 3.66m x 2.4m) that resembled a residential bedroom with one open doorway to the exterior. The fire was allowed to burn in post-flashover conditions for approximately 2 minutes. Clean burn damage located on the wall opposite of the door opening (not at the area of origin) extended from the floor to the ceiling and had an approximate 6-foot base. There was also an area of clean burn with angled lines of demarcation emanating from the area of origin.

Carman (2008) divided the room into four quadrants and performed a survey of the attendees in an attempt to derive an error rate study of investigators. He reports a 5.7% success rate of determining the correct quadrant where the fire was started. The Carman study did not provide the demographics of the attendees, nor did it provide any statistical rigor. Carman attributed the failure to the lack of understanding by the investigation profession of the differences between pre- and post-flashover fire behavior and resulting damage. The authors have since noted several limitations to this exercise including that the participants were not permitted to complete a full investigation of the compartment, were not allowed to move any items, and had to make a conclusion based on their visual interpretation of the damage from the doorway.

In 2009, Wolfe, Mealy, and Gottuk conducted fifteen full-scale tests with varying ventilation conditions and fuels. They focused on under-ventilated fires, the fire growth associated with these types of fires, and their forensic analysis. While much of the research was based more on the tenability limits and associated dynamics in under-ventilated fires, they reported on a few forensic-based conclusions. These included that soot deposition can be used to aid in the area of origin determination and that the clean burn area size was proportional to the fire size (Wolfe et al. 2009).

Carman reports on three tests conducted at ATF's fire research laboratory in a follow-up to his 2008 work (Carman 2010). The three tests were conducted with identical contents and ventilation. The compartment size, ventilation opening, and setup were similar to the 2008 work. The three tests were better instrumented with three total heat flux gauges, one radiant heat flux gauge, three gas sensors (measuring O_2, CO_2, CO), and gas velocity probes (Oullette 2008). The tests were able to burn in the full-room involvement state for 7, 140, and 111 seconds respectively. Each test fire resulted in damage along the wall opposite of the door opening, progressively greater in magnitude with the longer duration in full-room involvement burning. This area of damage opposite the door had angled lines of demarcation that extended from the floor to the ceiling. A clean burn area of damage was located at the area of origin only with the fire with the shortest duration of full room involvement burning. Clean burn damage also occurred along the wall near the doorway opening in the fire with the longest full room involvement burning duration.

A series of nine full-scale studies, funded by the National Institute of Justice, were conducted with ignitable liquid fuel spilled on carpeted and vinyl flooring with varying ventilation scenarios (Mealy et al. 2013). These tests evaluated many aspects of fire investigations, including the presence of ignitable liquid residue after extinguishment, fire patterns, depth of calcination, and the fire dynamics of an under-ventilated compartment. A compartment (3.7m x 3.7m x 2.4m) with a single doorway ventilation opening located in the center of a wall was used for this series of tests. An upholstered sofa and upholstered chair were located in adjacent corners across the room from each other with a coffee table in between. The ventilation opening was located in the wall opposite of this furniture. The ventilation opening was varied throughout the test between a slit vent (2m x 0.2m) and the full door opening (2m x 0.9m). Test one used only Class A fuels, while the eight remaining tests used gasoline as the first fuel ignited. The location of gasoline spilled was varied between the floor and on/around furniture items.

Some of their more notable findings was that floor patterns caused by ignitable liquids may be minimal because they can easily be destroyed, that the commonly reported clean burn damage may be caused by water spray from fire suppression hoselines, and that areas of clean burn were associated with the inflow of air due to local ventilation flows. Mass loss of the furniture items was measured at the end of each test and was showed to relate well to the area of origin. Areas along the wall surfaces that were white in color directly adjacent to areas of significant soot deposition were found within this series of tests to be attributed to the oxidation of the soot from the surface (i.e. clean burn) and with wash from the hoseline for suppression. Also, the study illustrated that drywall seams, if no tape and mud was applied, would present areas of clean burn damage during ventilation-controlled conditions (Mealy et al. 2013).

In 2011 three test fires were conducted that varied between single and multiple ventilation openings (Claflin 2014). The three compartments were similarly constructed measuring 11 feet, 5 inches by 11 feet, 9 inches (3.48m x 3.58m) with a ceiling height of 8 feet (2.4m). Each compartment had a door that measured 2 feet, 7 inches by 6 feet, 8 inches (0.787 m x 2.032 m) and was opened to the exterior for the entire duration of the test. Two tests also had a window that measured 3 feet by 4 feet in height (0.91 m x 1.22 m) with a 2 feet, 6 inch sill height (0.812m). The compartment was furnished as a residential living room with a couch under the window, armchair directly across the room from the door opening, an office chair adjacent to the doorway, and a coffee table.

The origin and ignition of the three tests were in a pillow placed along the back corner of the couch on the floor against the wall with the window. Each fire was said to have only burned for 2 minutes in full room involvement. Thermocouple data and total heat flux gauges were used as instrumentation for all three burns. Test 1 had the window and door open for the entire duration of the fire, test 2 had the window hinged closed until flashover and then the window was left opened for the duration of post-flashover, and test 3 had no window. These tests demonstrated similar findings as Carman's tests (2008) that significant heat flux and clean burn occurs on the wall directly across the room from the doorway. There was no significant damage identified around the window ventilation, as the researchers discussed that this vent served primarily as an outflow for the heated gases, while the doorway served as the inflow due to the location of the neutral plane. The researchers also concluded that the fire pattern at the true origin persisted in all three tests.

2.2.2 Fire Patterns

This section focuses on the literature that exists for fire patterns. This section has been divided into four subsections that evaluate the general location and type of fire patterns.

2.2.2.1 Geometric Shapes – Walls, Contents, and Ceiling Patterns

The principle behind fire patterns was first linked to the need to trace the fire spread (Rethoret 1945). All of the early texts indicate that fire tended to rise and that a pattern may exist from this damage, but most did not use the term pattern nor did they give any guidance on what a pattern was (Rethoret 1945; Kennedy 1962; Kirk 1969). The first use of the term pattern was in 1969 by Kirk when discussing the normal behavior of heated gases. However, Kirk elaborated on what the investigator should look for in evaluating this fire pattern when he stated "because of the upward tendency of every fire, some type of inverted conical shape is characteristic, the apex at the bottom being the point of ignition, with the fire rising and spreading" (Kirk 1969). Kirk continues the discussion by cautioning the investigator that this "pattern will be altered by the presence of obstructions, or of readily burned fuel in localized areas," and he warns that a very common complication arises when areas of excellent ventilation are present where "intense burns will be noted in such areas that may well distract the investigator from following the fire pattern back to its point of origin" (Kirk 1969). Consequently, Kirk can be credited as the first person to describe the damage by a fire as a geometric shape.

Kirk's three-dimensional conical shape persists today as the predominant means of evaluating the geometry of fire patterns. Only later did the literature express this conical shape as two-dimensional shapes, including triangular shapes, columnar shapes, V-patterns, U-patterns, and hourglass-patterns (Barracato 1979; Cooke and Ide 1985; Kennedy and Kennedy 1985).

The conical fire pattern theory evolved into a more systematized manner by the Kennedys (Kennedy and Kennedy 1985). The system was described as the truncated cone method, which described the fire plume as a three-dimensional cone that would be cut or truncated by the various two-dimensional horizontal and vertical obstructions (i.e. walls, ceiling, contents) within a compartment. The damage that would result would be dependent on the location of the origin of the plume and distance to the intersecting obstructions.

As explained in this method, the two-dimensional shapes and patterns would be formed by the overall three-dimensional plume as it intersected these surfaces resulting in V-shape and U-shape patterns on walls, contents and vertical structural member, and Radial-shaped patterns on the ceiling and horizontal obstructions. These researchers proffered that the closer the fuel item burning was to the wall surface, the sharper the contrast and angle to the lines of demarcation and the more likely the damage would resemble a V in shape. The further the fuel item burning was from the wall surface, the lines of demarcation would be more subtle in contrast and would be more round in angle in the shape of a U. Kennedys (1985) were also the first to propose that damage would be in the shape of a triangular, columnar, or conical shape after the flame plume had intersected a wall surface within a compartment.

There are a few misconceptions that have been promulgated over the years associated with V-patterns. The first is that the apex[1] of the V-pattern indicates an origin (Barracato 1979). Obviously, the damage to the walls remaining after the fire is the cumulative result of all items that burned and the investigator would not be able to tell if the damage witnessed was the first item or a later item burning (e.g. debris fall down). This misconception was dispelled in the first edition of NFPA 921 and is not prevalent within the current profession (Bieber 2014). The other more pervasive misconception dealt with the angle and base of the V-pattern. It was once thought that narrow V-patterns were produced by a fast developing fire and wide V-patterns were produced by a slow developing fire (Kennedy and Kennedy 1985). The other misconception stated that if the pattern had a wide base and resembled an inverted cone, then it was started with a liquid fuel (Barracato 1979). Both of these misconceptions have fallen into disrepute and are no longer prevalent within the current profession (Bieber 2014).

Other damage to walls commonly reported, that are not associated with the truncated cone discussion, are referred to as smoke and heat horizons. This damage is commonly reported as heat or smoke deposition reported to be found throughout a structure at varying heights on the walls of a room between areas of no damage and smoke or heat damage. This type of damage was first identified as being helpful at determining the area of origin by Straeter and Crawford (1955). In this text, it is stated that as "heat marks begin to form at the top of a room as a result of the hot air that rises from the fire…these marks get lower and lower on the wall. Wall condition on the four sides of a room may differ and thus indicate where most heat was applied" (Straeter and Crawford 1955). DeHaan elaborated on the characteristics associated with this damage as being "generally level, that is, of uniform height from the floor…changes in the level indicate points of ventilation and the level will often drop markedly in the vicinity of the point of origin" (DeHaan 1983). In over 40% of the fire pattern tests, level lines of demarcation attributed to this damage was identified.

Truncated cone fire patterns have been found in over 50% of all fire pattern tests. Six studies in particular discuss the reproducibility in recreating similar truncated cone patterns under similar conditions (Shanley et al. 1997; Hicks et al. 2006; Hicks et al. 2008; Gorbett et al. 2006; Hopkins et al. 2007; Madrzykowski and Fleischmann 2012). A few of the studies also indicated that truncated cone patterns, specifically V-patterns, were located away from the true origin causing confusion for the investigators (Hoffmann et al. 2003; Carman 2008; Carman 2010; Tinsley and Gorbett 2013).

[1] Of course, apex is actually the antonym of the word desired here. The correct word is nadir, but to remain consistent with these texts apex will be used.

Figure 2-6: Photograph of a Conical-Shaped Fire Pattern along a concrete block wall (fire origin was located under the stack of wooden pallets-fire test conducted at EKU by author)

2.2.2.2 Floor Patterns

Fire patterns identified on the floor have been a common theme within fire investigation as being a possible indicator that flammable or combustible liquids were used within the fire (Smith 1983; Beyler 2009). In fact, a recent sentinel event analysis of wrongful convictions found that this one misconception is the most common factor in wrongful arson convictions (Bieber 2014). This misconception persists despite the warnings from both the fire science and fire investigation communities (Shanley et al. 1997; NFPA 2014; Gottuk and White 2008).

Many of the first texts on fire investigation discussed the concept of low burning and the importance of evaluating the floor for fire patterns (Kennedy 1962; Kirk 1969). In these texts the authors stressed that the investigator should evaluate low burns for possible ignition sources, but did not necessarily link the damage to ignitable liquids. In fact, Kirk was very adamant that investigators should not conclude that the damage was from an ignitable liquid as "such an interpretation was more often incorrect than otherwise" (Kirk 1969).

However, other texts of the time indicated that damage to floor was an indicator of arson (Battle and Weston 1960; Fitch and Porter 1968). Obviously this misconception was widespread as Kirk identified that it was "not uncommon for the investigator to assign the cause to the use of a flammable liquid" (Kirk 1969). More than a decade later this misconception can be seen in the majority of all fire investigation literature (Barracato 1979; DeHaan 1983; Smith 1983; Harmer et al. 1983; Kennedy and Kennedy 1985; Cooke and Ide 1985). The majority of these texts stated that the investigator should consider the damage to be caused by an ignitable liquid if the investigator would visibly observe damage to the floor in the shape of a puddle, have hard-edged burn marks in the shape of a pour, or the damage had the appearance of trailers (i.e. long lines of damage appearing to spread the fire from one location to another). However, most of these documents also cautioned against relying solely on the use of visible observations and encouraged the investigator to take samples of fire debris for analysis.

In the mid-1980's there began a trend in the literature that spoke out against this misconception and began to provide a list of alternative explanations of damage to the floor (DeHaan 1983; Taylor 1985; Taylor 1986; DeHaan 1987; Eaton 1987; Wood et al. 2012). The studies demonstrated that the following causes could result in damage similar to irregular floor patterns, including: fires from interstitial space below the floor decking, melting plastics, draperies, furniture items, ventilation path, and radiant heat from fully developed fires. NFPA 921's original publication followed this trend and warned, "irregular, curved, or 'pool shaped' patterns on floors and floor coverings cannot always be reliably identified as resulting from ignitable liquids on the basis of observation alone" (NFPA 1992). Notice, however, none of these documents came out and directly stated that an investigator could not identify an ignitable liquid from a floor pattern based on observation, they only warned that it "cannot always be reliably identified" (NFPA 1992). This warning was strengthened over the years to say "irregular, curved, or 'pool shaped' patterns on floors and floor coverings should not be identified as resulting from ignitable liquids on the basis of observation of the shape alone" (NFPA 2001).

There have been a few studies performed that specifically evaluated the fire pattern creation on the floor (Putorti 2001; Mealy et al. 2013). Putorti (2001) performed a series of experiments that evaluated the damage to a variety of floor surfaces (carpet, wood, and vinyl) with varying volumes of ignitable liquids used in the open. He evaluated gasoline and kerosene. He concluded that it was possible to identify the quantity of fuel used by the burn area. These tests were not conducted within a compartment. Mealy et al. (2013) conducted a series of compartment fire tests with ignitable liquids poured and evaluated the persistence of such a pattern through a compartment fire. They found that that floor patterns caused by ignitable liquids might be minimal because they can easily be destroyed and because the short duration of exposure due to fuel consumption.

Floor patterns were found lacking in many of the fire pattern tests where the compartment transitioned to a fully involved state (Shanley et al. 1997; Wood et al. 2012; Mealy et al. 2013). However, some data exists that indicates if a compartment fire does not transition to a fully involved state, then the floor patterns may persist (Putorti 2001; Mealy et al. 2013).

A study conducted in 2012 examined the effect of carpet underlayment/carpet pad on post-flashover fire, floor patterns (Wood et al. 2012). Specifically, the hypothesis that carpet pad seams could mimic the floor fire patterns previously attributed to ignitable liquid pours was examined. Fire tests in a scaled compartment using a propane sand-burner were designed to rapidly progress through flashover with a short period of full room involvement. Instrumentation included thermocouples in the gas layer and under the flooring material. Multiple carpet pads were tested. Carpet pad configuration was also varied including no seam and two, off-center seams for comparison and control purposes. Additional comparison and control samples were generated using ignitable liquid pours that achieved post-flashover conditions without use of the burner, but with the burner in place to maintain test consistency. A subset of replicate tests was also performed. Post-test data collection included examination, photography, and a subset of depth of char measurements. Preliminary results indicated the ability to generate similar although not identical floor burn patterns between carpet pad seams and ignitable liquid pours.

Figure 2-7: Scene photograph of suspected ignitable liquid pour (Wood et al. 2012)

Figure 2-8: Testing photograph for carpet pad seam generation of pattern similar to reported ignitable liquid pour showing burning in exposed surface resulting from carpet pad shrinkage (Wood et al. 2012)

Figure 2-9: Resultant floor burn pattern from carpet pad seam without use of ignitable liquids (Wood et al. 2012)

2.2.2.3 Undamaged Areas

The lack of damage has often times been overlooked in most discussions related to fire patterns. The investigator has always been tasked to evaluate damage from lesser to greater with minimal advice related to any meaning that exists for the lack of damage or the lesser damaged areas (Rethoret 1945). Several of the early texts described using undamaged areas on the floor or walls to help with reconstruction of contents within the compartment (Kennedy 1962; Kirk 1969). This is still a common practice in fire investigations with these undamaged areas termed protected areas.

Custer was the first to discuss a concept of shadowing by content items and how these areas of lesser damage assisted the investigator in identifying direction of heat exposure (Custer and Wright 1984). Later the term morphed into heat shadowing, which was first defined as "the effect of an object blocking the convected or radiated travel of heat and flame from its source to the particular surface material which is under examination" (Kennedy and Kennedy 1985).

Heat shadowing and protected areas were shown to assist investigators in determining that the fire did not originate behind certain contents (Shanley et al. 1997; Gorbett et al. 2013; Claflin 2014).

2.2.2.4 Penetrations

Holes in floors have had many misconceptions tied directly to floor patterns, as discussed previously. The same proponents of identifying 'pour patterns' as being indicative of an ignitable liquid, also promulgated that holes in floors were indicative of ignitable liquids being used (Battle and Weston 1960; Fitch and Porter 1968; Barracato 1979; Smith 1983; Harmer et al. 1983; Kennedy and Kennedy 1985; Cooke and Ide 1985). Kirk being one of the few texts at the time that opposed this idea when declaring "flammable liquids never carry fire downward" (Kirk 1969). As floor patterns were warned against, so has floor penetrations by both the fire science and investigation communities (Babrauskas 2005; NFPA 2014). Alternative explanations are now commonly given when discussing penetrations through floors, including: radiant heat, furniture items, melting plastics, and pre-existing openings in the floor during fully involved compartment fire (NFPA 2014).


Figure 2-10: Photograph of penetration through a floor

Other penetration patterns have arisen, which dealt more with determining the direction of fire spread from top down or bottom up. There have been many references to penetrations through floors within the early texts on fire investigations, but few provided any guidance on how to interpret from the damage if the fire was moving up through the hole or down. The first discussion on this came in the form of discussing beveling or loss of mass (DeHaan 1983). Illustrations from this first discussion are still found today in the current edition of NFPA 921 showing a cross-section of a floor with greater beveling or loss of mass indicating direction (NFPA 2014). The current damage indicator as espoused by NFPA 921 is that "sides that slope downward from above toward the hole are indicators that the fire was from above. Sides that are wider at the bottom and slope upward to the center of the hole are from below" (NFPA 2014).

Babrauskas (2005) lists several unpublished tests of holes through wood floors and provides a summary of these tests.

2.3 Literature on compartment fire dynamics influencing damage

The damage observed to wall, ceiling, and content surfaces is an artifact of the fire dynamics for that fire. Identifying the cause of the damage is complicated by the fact that the investigator has to use evidence after the event, such as the location and magnitude of damage, compartment geometry, ventilation openings, and the position and number of fuels as a means to identify the range of initial conditions that may have influenced how the fire developed. Because of this, the problem of using fire damage to determine how the fire developed is considered an inverse problem. Other areas of science regularly deal with inverse problems typically through extensive mathematical study. However, most inverse problems are approached by first establishing direct solutions for well-posed problems. Therefore, the approach of this step is to leverage what science currently exists to assist with validating the current list of direct solutions for fire pattern generation and identifying characteristics that may exist and how they may vary with the changing fire dynamics. The direct solutions currently listed for causes of fire patterns include, plume-generated patterns, hot gas layer-generated patterns, ventilation-generated patterns, and suppression-generated patterns (NFPA 921 2014).

In this section of the literature review, sections 2.3.1.1-2.3.1.2 discuss the basic causes of fire patterns and will serve as the connection of fire investigation terminology to the fire science research that has been conducted in those areas. Section 2.3.2.1-2.3.2.5 will outline the characteristics that are currently being used by fire investigators in determining the cause of the fire pattern and evaluate the findings of the fire pattern studies.

2.3.1 Causes of Damage

The investigator typically assigns an interpretation to each fire pattern as to how it may have been created, which in turn assists the investigator in determining how the fire spread. This process has significant potential for uncertainty, as the initial conditions are generally unknown to the investigator.

NFPA 921 states that there are "three basic causes of fire patterns: heat, deposition, and consumption" (NFPA 2014). Consumption is a function of heat transfer and the material properties. As such, material properties were already discussed in the degree of fire damage assessment and will not be duplicated here.

2.3.1.1 Cause of Damage – Heat

The cumulative heat exposure should be considered the leading factor in the creation of damage. The cumulative heat exposure consists of the duration and varying intensity of heat exposure to the materials. Heat exposure to the materials (e.g. plastics, wood) will result in either physical or chemical changes. Physical changes include melting, deformation, expansion, or loss of tensile strength. Chemical changes include the decomposition/pyrolysis, dehydration, or changes in color.

Heat damage to the surface linings and the contents within the compartment after the fire is frequently the most readily visible and measurable. The effects that remain after a fire are typically related to the damage resulting from the cumulative heat flux received by an exposed material. The developing fire and the variables influencing the fire scenario control heat transfer in a compartment, including the location, the intensity, and duration of the heat transfer. The dominant sources for heat transfer during a compartment fire stem from the following:

1. Flaming Combustion
    a. Fire plume associated with a burning fuel item/package

b. Flame spread over/through a material
c. Diffusion flames where the fuel and air mix at the combustion site (i.e. flaming combustion detached from the fuel item or package)

2. High temperature combustion gases
    a. Ceiling jets
    b. Upper layer gases
3. High Temperature lining surfaces – Radiant heat transfer (absorption/reflection)

As heat transfer is first and foremost dependent on a temperature difference, greater temperature differences will result in greater heat flux. In a compartment fire, the highest temperatures are present at those locations where flaming combustion is occurring. The fire plume and the various heat fluxes generated by it are one of the primary means of damage production in the early stages of a fire due to this great temperature difference and highly turbulent flows. Fire plumes against wall surfaces have shown to have moderate heat fluxes ranging from 40-80 kW/m^2, while heat fluxes measured in tests with objects immersed in diffusion flames range between 75-200 kW/m^2 (Qian and Saito 1992; Dillon 1998; Lattimer 2008). Incident heat flux to wall, floor, or ceiling surfaces is dependent on the HRR of the fuel and standoff distance between the flame plume and the surface of interest. The greater the distance between the base of the plume and the surface of the wall or content surface will result in a substantially decreased heat flux to the surface (Qian and Saito 1992). Saito (1993) and Williamson, et al (1991) witnessed a 50-70% decrease in peak heat flux values when small standoff distances (0.05-0.25 m) were employed.

The flame plume is also the most predominant contributor to damage and ignition of secondary and tertiary contents early in the fire prior to the contribution by the upper layer (Jahn et al. 2008). There has been much work towards developing methods for calculating the radiant heat transfer from a plume to secondary objects outside of the plume with varying accuracy. The bulk of this research can be found within the SFPE Engineering Guide, "Assessing Flame Radiation to External Targets from Pool Fires" (SFPE 1999). Many calculations are focused on simplifying geometric shapes, such as cylinders, cones, planes, and point targets.

One aspect of looking at radiant heat flux is to determine if the secondary object has been raised to a critical temperature or is receiving a critical heat flux where ignition of that object is possible. In the fire investigation profession, testing to determine whether the first burning object can ignite a secondary object is paramount to hypothesis testing of an area of origin. Equally important is to determine whether the radiant heat transfer is sufficient to cause damage to nearby contents or wall surfaces.

Some experimental work has been conducted in this area as well as predictive calculations (Jahn et al. 2008). Theobald (1968) performed a series of experiments with target combustible items (wood blocks, cotton cloth, and plywood) located at 0.45 m and 0.9 m above the floor at various lateral distances away from a variety of common residential fuel items burning, such as a kitchen chair, easy chair, arm chair, bookcases, and wardrobes. He then recorded the maximum lateral distances at which the target fuels were scorched, charred, or ignited. Items were scorched at distances greater than 0.19-1.2m depending on the material and heat source.

Babrauskas (1981) reports on ignition of secondary items based on burning a series of common residential fuels and evaluating the heat flux to transducers at varying lateral distances. He reports

> "irradiances measured 0.05 m away range to near 80 kW/m^2 for the fastest burning specimens; however, 40 kW/m^2 was not recorded farther than 0.44 m away and 20 kW/m^2 was not found beyond 0.88 m distant. The implication is that common furnishing items, which normally require a minimum irradiance approaching 20 kW/m^2 for ignition, would stand little hazard of fire involvement if placed at least 1 m away from the initial source" (Babrauskas 1981).

These findings were reported as only being applicable for pre-flashover fires. More recent research has identified heat flux values between 25-50 kW/m^2 reported at 1 m away from more modern fuel packages, including king size mattresses, upholstered chairs, and sleeper sofas (Madrzykowski and Kerber 2009).

The collection of high temperature gases within a compartment is also a source of heat flux that can cause damage. A ceiling jet is formed by the intersection of the plume with the ceiling, which will cause greater heat to be transferred first to the ceiling surface and later to the intersecting wall surfaces. The temperature of the plume will be greatest near the plume centerline and therefore the greatest heat flux to the ceiling surface will be at this location at this point throughout the duration of the fire. The temperature and resultant heat flux decreases with increasing radial distance from the plume centerline. In addition, the ceiling jet velocity is highest near the centerline of the plume and decreases as it moves outward (Heskestad 2008). Consequently, these two factors combine to inflict more damage and create more pronounced fire effects near the plume centerline, with the damage decreasing as the distance from the centerline is increased (Jowsey 2007). When the flame plume has not intersected the ceiling, heat fluxes along the ceiling surface near the centerline of a plume have been recorded to range between 80-100 kW/m^2 within 0-1 meter radial distance, while heat fluxes between 1.0-1.6 meter radial distances ranges between 10-70 kW/m^2 (Dillon 1998; Lattimer and Sorathia 2003).

As the fire continues to develop, the ceiling jet and the gases from the upper layer begin to have an intensified effect on the surfaces nearest the plume. Later in a fire's development, an upper layer begins to form and starts transferring heat to the wall and ceiling surfaces. The energy generated by the fire and therefore the temperatures and layer depth of the upper layer vary as a function of time (Walton and Thomas 2008). Thus, different locations within the compartment may be receiving different temperatures at different times throughout the fire. However, an assumption can be made for fuel-controlled fires that higher temperatures will occur at the plume interface with any building or content's surface. As the temperature of the gases in the upper layer increases and the duration of influence between these gases and the lining surfaces increase, the heat flux imposed on these surfaces reaches a critical threshold that begins damaging the material and creating fire effects attributed to the upper gas layer. Heat fluxes to the walls inside a compartment containing an upper gas layer have been reported to range between 5-40 kW/m^2, based on varying temperatures between 200-600^{o}C (Tanaka et al. 1985).

Drysdale (2011) indicates that the average compartment temperatures are highest near the cross over between fuel-controlled and ventilation-controlled. The fires that are located at the extremes of the spectrum (i.e. predominantly fuel-controlled or ventilation-controlled) produce substantially lower temperatures. Consequently, the damage expected in a fuel-controlled state is generally less-severe until the ventilation begins deteriorating, nearing the cross over to ventilation-controlled. Furthermore, average fire gas temperatures have been related to the ventilation factor compared to the total surface area of the compartment, commonly denoted by $A_v\sqrt{H_v}\,/A_T$. This relationship points out that there are higher gas temperatures reached in the fuel-controlled burning but the duration of burning is shorter because "much of the heat energy is transferred out of the room by the air/fire gas exchange" (Drysdale 2011).

There has been extensive work done in the area of flashover for traditional residential-sized compartments with a single opening. Several correlations have been developed to assist in determining the minimum HRR necessary for flashover to occur, conditioned on the total surface area of the compartment (A_T) and the ventilation factor $A_v\sqrt{h_v}$ (Babrauskas 1980; McCaffrey et al. 1981; Thomas 1981). As the compartment transitions through flashover and into full-room involvement, the upper layer descends toward the floor and encompasses nearly the entire volume of the compartment. Therefore, the walls, ceiling, and floor surfaces are now receiving an elevated heat flux, in addition to the already burning fuel receiving greater feedback, increasing its own HRR, and other fuels becoming involved. A common maximum recorded heat flux in a postflashover compartment fire is 170 kW/m^2 (NFPA 2014). Each fire pattern study has the three most common flashover correlations summarized within the excel spreadsheet.

During a fully involved compartment fire or when a compartment fire is ventilation-controlled, more complete combustion is achieved at those locations where the mixture is adequate. Several studies concerning ventilation-controlled fires throughout the years have introduced a concept of a ventilation factor ($A_v\sqrt{h_v}$) and illustrated the importance of ventilation openings on a fire's growth by analyzing the size of ventilation openings, locations of these openings within the compartment, and the shear mixing that occurs at the interface of the opening (Kawagoe 1958; Thomas and Heslden 1972; Harmathy 1972; Thomas and Bennets 1999; Utiskul 2007; Sugawa et al. 1989; Quintiere 1995). Many of the studies discuss the production of unburned hydrocarbons (UHC's) during under-ventilated conditions that result in unburned fuel filling the compartment and undergoing combustion only where sufficient UHC concentrations encounter sufficient oxygen (Beyler 1984; Utiskul 2007; Thomas and Bennets 1999).

Not all compartment fires will transition through flashover (Drysdale 2011). The compartment can reach a state of full-room involvement without transitioning through flashover, or become ventilation-limited and never achieve full-room involvement state (Francis and Chen 2012). One of the most important findings is that combustion was found to occur detached from fuel items and found to burn nearest the open ventilation source if the global equivalence ratio (ϕ) in the fire room becomes larger than unity, typically between 1.2-1.6 depending on temperature (Thomas and Bennets 1999; Utiskul 2007). ϕ is defined as the average fuel-to-oxygen mass ratio in a compartment divided by the stoichiometric value in a compartment (Wieczorek et al. 2004).

The fire is generally regarded as well-ventilated when values of $\phi < 0.3 - 0.5$. The combustion within this compartment is of a high efficiency and the yields of soot and carbon monoxide (CO) are low (Pitts 1994). The fire is considered to be under-ventilated at higher values of $\phi > 1.0$. Typically, flashover occurs at a $\phi = 1.0$ (Wieczorek et al. 2004). Gottuk (1992) reports sustained external burning occurring at ϕ values around 1.4 +/-0.4, but other research has reported extension of flames outside the compartment starting at ϕ values of 0.7 (Wieczorek et al. 2004). Gottuk's (1992) results were gases from the layer burning and escaping, while Wieczorak (2004) had flames resulting from a lack of mixing within the compartment, which has also been identified in compartments with combustible linings (Drysdale 2001). As the combustion zone is not attached to a fuel item or fuel package any longer, it becomes more difficult for the fire investigator to evaluate whether the damage was caused by a flame plume burning attached to a fuel item or if it is the UHCs burning detached from a fuel item due to ventilation-controlled conditions. Therefore, determining if and when the fire transitions from a fuel-controlled to a ventilation-controlled condition is an important distinction.

As the effects of ventilation have been shown to significantly influence damage within the compartment, a further review of these concepts is necessary. Hydrostatic pressure differences at the ventilation opening cause the hot gases to exit the compartment and cooler air to be transferred into the compartment, assuming no external force is causing a greater pressure. The natural convection drives air out of the compartment creating a lower pressure for inflow to be driven from gravity flows or can also be influenced by wind or other mechanically induced flows (e.g. positive pressure ventilation). The mixing of the air and UHCs has been shown to occur at the opening, along the gravity flow, around objects within the flow, and opposite the opening along walls, specifically for doors (Abib and Jaluria 1992; Quintiere and McCaffrey 1980).

Quintiere and McCaffrey (1980) showed that near-opening mixing associated with the cold, incoming air flow entraining the hot gas is an issue that would be a potential cause for near-to or adjacent damage occurring on surfaces next to ventilation openings. Abib and Jaluria (1992) showed that the entering airflow could cause mixing through wall flows and mixing to occur opposite the ventilation opening with a single doorway. The velocity of this air inflow also influences this mixing.

The average velocity of natural buoyancy driven flows or natural ventilation through the bottom of a door during ventilation-controlled conditions is approximately 1.5-2.0 m/s (3.4-4.4 mph) (Kerber 2010; Quintiere and McCaffrey 1980). Average velocities of natural ventilation flows through windows have been recorded between 0.5-1.0 m/s (1.1-4.4 mph) depending on the sill height and elevation of the opening within the wall (Kerber 2010; Kerber and Walton 2005;

Quintiere and McCaffrey 1982). The square root of height of the opening is the relevant determinant of the max velocity (Babrauskas 1980; Quintiere 1995). The reported velocity of flows from wind-assisted or mechanically induced flows through the bottom of a door and window can be on the order of 10 m/s (22 mph) (Kerber and Walton 2005; Madrzykowski and Kerber 2009).

Other factors that have been shown to influence the HRR within a compartment and the location of combustion are suppression-related activities that affect ventilation. The ventilation of the compartment for suppression is a common activity by fire department personnel, typically performed by opening doors and windows. Often times, positive-pressure ventilation, or mechanically induced ventilation, through the use of a fan is employed in conjunction with fire suppression activities. This change in ventilation is typically done during ventilation-controlled conditions, which causes the HRR to increase within the compartment and results in combustion wherever the mixture of UHCs and oxygen is sufficient, and that the mixture be at a sufficient temperature to initiate combustion (Madrzykowski and Kerber 2009; Kerber and Walton 2005).

2.3.1.2 Cause of Damage – Deposition

Exposure of materials to the byproducts of combustion can also lead to damage that may be useful to the investigator. Smoke contains particulates, liquid aerosols, and gases (NFPA 2014). The deposition of smoke/soot onto surface linings and contents within an enclosure stems from the following:

1. Fluid flows – Temperature and velocity of the gases colliding with cooler surfaces (thermophoretic forces).
2. Distance from the area(s) of combustion

Combustion that fire investigators will most commonly encounter is predominantly diffusion flames. The combustion of a fuel through diffusion flames is inherently oxygen limited by the diffusion reaction and the availability of only 21% of oxygen in air in well-ventilated fires. This limitation of the flaming combustion allows for the production of smoke. Smoke consists of liquid aerosols, solid particulates (i.e. soot), and gaseous byproducts, including carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN), oxygen (O_2), steam (H_2O vapor), and unburned hydrocarbons (UHC). This production of incomplete combustion byproducts is exacerbated in poorly ventilated spaces, ventilation-controlled burning regimes, and combustion of fuels that under normal atmospheric conditions have high soot yields (e.g. aromatic and unsaturated hydrocarbons).

The liquid aerosols, soot, and other particulates are in motion due to the buoyant nature of the heated gases. As this smoke collides with cooler surfaces, it may deposit out of the heated gases onto wall, ceiling, and content surfaces. The amount of soot deposited is dependent greatly on the thermophoretic forces and by soot losses throughout the building (Riahi 2011; Riahi 2012; Riahi et al. 2013; Wolfe et al. 2009).

Thermophoretic forces between the gas and surface lining are greatly dependent on the burning regime of the fire. In the early stages of a fire and through fuel-controlled conditions, the production of the incomplete combustion byproducts (HCN, CO, UHCs) is typically minor. The production increases substantially as the compartment fire becomes ventilation-limited. The higher temperatures and higher velocities of smoke cause greater collection of soot deposits to form in certain locations within the compartment. As the temperatures are higher in the room of origin it is expected that an upper layer will be affecting those surfaces higher in elevation. Conversely, as the smoke moves away from the room of origin the temperatures will decrease, which causes the smoke to descend within the compartment causing lighter soot to deposit across the entire elevation of wall surfaces. Therefore, it is expected that soot deposition on wall surfaces to be greatest in thickness and higher in elevation closer to the room of origin and lesser in thickness and lower in elevation as one moves away from the room of origin. Often times the soot deposited within the room of origin will be higher in elevation with distinct lines of demarcation and thick soot deposits. Soot deposited in rooms away from the room of origin have a fairly uniform soot deposition on all surfaces extending from floor to ceiling (Wolfe et al. 2009).

Riahi (2012) studied the soot deposition characteristics of three different fuels in bench-scale experiments and then against a gypsum wallboard lined wall. An optical measurement method was developed to arrive at optical properties of smoke deposited out of a smoke layer onto glass filters. From this work, the researchers used gravimetric measurements of these filters to demonstrate and validate an analytical model for smoke deposition based on thermophoresis.

2.3.2 Characteristics of Direct Solutions

The characteristics of damage that have been reported in the literature to assist investigators in determining the cause of the fire pattern will be evaluated here.

2.3.2.1 Plume-Generated Fire Patterns (PG Patterns)

Fire plume generated fire patterns are the most important to identify correctly. The fire origin will ultimately be connected to a plume generated fire pattern. However, if the fire pattern is incorrectly assigned as a plume generated pattern, then the entire origin hypothesis will most likely be incorrect (Carman 2008).

The fire plume is typically the highest temperature zone within the compartment, which can lead to significant damage (Beyler 1986; Lattimer 2008). In fuel-controlled fires, the greatest damage within the compartment is typically found near fuel item(s) or fuel package(s) that have undergone combustion. As discussed in Section 2.3.1.1, those surfaces that have direct flame contact will have the highest heat flux exposure, followed by fire plumes near surfaces. However, all of this is dependent on the burning regime and where combustion is actually taking place at the point in time during the fire when the fuel was ignited.

As with anything, there are additional caveats in the identification of plume-generated fire patterns. The first of which is the standoff distance between the fuel item burning and the damaged surface. Shanley (1997) reported one of the driving factors for the lack of a plume-generated fire pattern associated with the origin in a chair was due to the chair being placed approximately 18-inches away from the wall.

Plume-generated fire patterns are commonly associated with a greater magnitude of damage (NFPA 2014). Therefore, the fire effect itself may provide a basis for determining what degree of heat flux and/or duration is required to cause the effect. For example, many materials must reach certain temperatures to melt, deform, or fail. If the temperatures are high enough to cause such damage, then it is likely that a plume caused the effect. For example, the clean burn effect requires wall temperatures to reach approximately 450-500°C and should be evaluated as possibly exposed to a plume (Stratakis and Stamatelos 2003).

NFPA 921 (2014) discusses that plume-generated patterns typically have characteristics associated with geometric shapes. Fire investigators have used geometric shapes, such as truncated cones, triangular, columnar, conical, v-shaped, u-shaped, and hourglass-shaped patterns since the early 1940's (Rethoret 1945). Every fire investigation text, including NFPA 921, uses shapes to describe the characteristics of the lines of demarcation associated with plume-generated patterns. There are only two studies that have focused solely on the geometric shapes from plumes (Hicks et al. 2006; Hicks et al. 2008); although, most fire pattern studies listed in Section 2.2.1 use shapes as descriptors.

Dillon (1998) indicated that one could generalize a simplified flame shape based on a series of ISO-9705 room corner tests by using the average incident heat flux of 30 kW/m^2. He found that the damage from the flame plume would extend approximately the width of the fuel for 100 kW fires that did not have a ceiling jet form, and 3 times the width of the fuel with 300 kW fires that did have flame extension under the ceiling. Dillon (1998) went on to illustrate that some of the corner flame height approximations resulted in 40% uncertainty, but others were as close as 2%.

Madrzykowski (2012) completed work on flame plume damage against a gypsum wallboard lined wall and showed that for smaller HRR fuels (20-80kW) the maximum width of damage was never greater than 1.5 times the width of the fuel. His work also determined that the height of the plume damage was within 5% of the mean visible flame heights for the natural gas burner and gasoline fires. Comparing Delichatsios's (1984) simple correlation of flame height for wall fires to the average damage height identified in Madrzykowski's study shows that the calculated flame height under-predicted the damage height by approximately 7-11% for the natural gas burner and gasoline fires.

Fire investigation texts describe the characteristics of the lines of demarcation associated with a plume-generated pattern as a progression through triangular, columnar, and conical patterns. The inverted cone or triangular pattern resembles an upright triangle with the vertex at the top. This pattern has been associated with a fuel package that has the potential HRR to overcome the thermal inertia and start a pyrolysis reaction in the surface material, thereby creating the pattern, but insufficient energy to produce a plume which reaches any horizontal restriction above the fuel package (Hicks et al. 2008; Madrzykowski 2012; NFPA 2014). This has been provided as the reason for a visible area remaining that exhibits heat exposure, which has a sharp leading edge of demarcation widening significantly at the base forming a triangular shape or pattern.

Largely parallel vertical lines of demarcation and a HRR sufficient to reach any horizontal restriction above the fuel package have been provided as the reason for columnar patterns (NFPA 2014). A columnar pattern has been described as a visible pattern where the leading front, or sharp leading edge of demarcation from a triangular pattern, has continued to spread with the rising heat and other products of combustion and has reached an intersecting horizontal surface (Hicks et al. 2008).

A conical pattern has been characterized as one that is produced when the interacting buoyant fire plume is restricted by an intersecting horizontal surface, spreading the heat across the bottom of the obstructing surface. The surface then redirects the buoyant flow and its momentum across the bottom of the ceiling creating a ceiling jet, which begins to descend from the ceiling as an upper layer (Hicks et al. 2008). This causes the plume to widen horizontally in the upper layer causing damage to the intersecting surfaces. A two-dimensional fire pattern is expected to form on the vertical surface interface (i.e. walls) in the form of a funnel or cone with the vertex at the bottom. This fire pattern has been proposed to indicate a fuel package that has reached a HRR sufficient to create a flame plume that reaches the horizontal surface (i.e. ceiling).

As vertical and horizontal surfaces intersect this 3-D fire plume, truncated conical shaped patterns have been shown to form (NFPA 2014). If the burning fuel package was located at or very near the vertical witness surface, then the expected fire pattern is shaped as a "V", evidenced by its angulated lines of demarcation. If the burning fuel package was located away from the witness surface, the resulting fire pattern has been characterized as being in the shape of a "U", evidenced by its radial or curved lines of demarcation (Hicks et al. 2008; NFPA 2014).

Several myths have been associated with geometric shapes that cause investigators pause before using the shapes as descriptors. For example, one myth was that an investigator could determine the speed of the fire by looking at the width of the v-pattern. Another myth is that at the base of every v-pattern is an origin. These myths have been dispelled by several studies, but their influence on using the geometric shapes as descriptors has justifiably persisted (NFPA 2014; Shanley et al. 1997).

Another problem is that the shapes discussed are assuming an idealized fire plume that is shaped as a cone, which is a gross oversimplification. Shanley (1997) described the phenomenon that ventilation to the room was able to change the truncated cone shape expected from the flame and fire plume by "leaning or pushing of one side of the pattern away from the source of ventilation" (Shanley et al. 1997). Airflow from a ventilation opening has been shown in previous compartment fire studies to cause flames to lean over significantly and that the influence of this factor decreases as the plume is moved back away from the vent (Steckler et. al 1982; Mealy et al. 2013). As such, the recognition and identification of lines or areas of demarcation and the elevation changes with those lines of demarcation capture the essence of these shapes without using geometric shapes as universal descriptors.

In summary, the characteristics distilled from the literature is that plume-generated patterns have areas of greater magnitude of damage in relationship to the surrounding areas and because of this the lines of demarcation between these areas are described as clear or sharp. Also, the lines of demarcation are not parallel to the floor or ceiling, but are at an angle representing the buoyant flow, usually with characteristic geometric shapes.

Figure 2-11: Photograph of a Plume-Generated Fire Pattern (fire origin was located at the base of this damage-test conducted at EKU by author)

2.3.2.2 Upper Layer-Generated Fire Patterns (ULG Patterns)

The upper layer is a term commonly given to the collection of smoke and heated gases during the progression of the fire near the upper regions of the compartment, typically near the ceiling. The high temperature gases and soot in the upper layer influences the patterns formed on lining materials of the compartment and contents. The damage caused by this upper layer is often times referred to as hot gas layer-generated fire patterns or heat and smoke horizons (NFPA 2014; DeHaan 2012), but in this work it will be described as upper layer-generated patterns (ULG patterns). The literature identified that investigators use the damage in two different ways. First, the upper layer-generated fire patterns are used by investigators in determining the extent to which the upper layer has descended in the compartment and that, because it is a heat source, is used to help describe other areas of damage within the compartment.

Secondly, these patterns are often used as a means to show direction of smoke and heat travel.

The ULG patterns are characterized by level lines of demarcation (or lines with similar elevation) with a generally uniform degree of damage (NFPA 2014). Noted differences with this level line of demarcation are damage in corners and near ventilation openings. Hicks (2008) noted that the lines of demarcation throughout the compartment would descend in elevation dependent on the header depth and type of opening, except the line of demarcation would descend lower in corners and ascend near ventilation openings.

The upper layer gases are elevated in temperature and have the ability to radiate heat downward onto the tops of contents throughout the compartment. Fire investigators describe this consistent damage to tops of contents as radiant heat damage being caused by the upper layer. Correspondingly, this heat source is often attributed to igniting contents throughout the compartment, especially those items located relatively high in elevation around the compartment (e.g. curtains). Fire investigators commonly use the lack of thermal damage behind or under contents, known as protected areas, as evidence that the damage was caused by an upper layer.

Investigators use the varying heights and direction of the lines of demarcation as indicative of directional flow. Direction of flow is typically associated with the lower line of demarcation being closer to the origin of the flow. These patterns are often witnessed on vertical surfaces of content items and wall linings. The cited basis for this pattern is the principles of fluid flow and the buoyant nature of heated gases. This is the reason that many fire investigation texts commonly refer to fire moving up and outward (DeHaan 2012; Kennedy 1962; Kirk 1969; Rethoret 1945).

When the gases rise and expand, they begin interacting with the lining surfaces and contents in the flow of the fluid. Particulates and aerosols are deposited and heat is transferred in the same direction and flow as the smoke. As the gases rise and expand, they also begin to interact with ventilation openings. The movement of smoke from a compartment into an adjoining space is controlled by the density differences at the interface of the ventilation opening. Upper layer gases inside the compartment are driven by density differences due to their higher temperature and lower density. These gases are buoyant compared to the surrounding air at the opening interface, which causes them to flow through the opening, unless there is wind or some other external force (mechanical ventilation) allowing the pressure outside of the compartment to be higher. Therefore, the dynamic forces that drive flow through an opening are based on fluid dynamics and fluids in motion at the ventilation opening interface and the discharge characteristics of the opening. As the smoke exits the opening, it expands in volume and rises. Particulates and aerosols are commonly deposited on the wall and ceiling surface where the upper layer interacted with the lining surface (NFPA 2014). In addition, if these gases were undergoing flaming combustion as they exited the opening, thermal damage to the wall surface is expected to follow the same theory (DeHaan 2012). The resulting damage appears to be angled lines of demarcation with the lower end of the line of demarcation being nearest the source of the smoke flow.

Figure 2-12: Upper Layer-Generated Fire Pattern (fire origin was located along adjacent wall-fire test conducted at EKU by author)

Characteristics distilled from the literature related that the ULG patterns will have level lines of demarcation with relatively uniform magnitude of damage, unless the upper layer is flowing from one location to another and, if so, the lines of demarcation will be angled towards the opening.

2.3.2.3 Ventilation-Generated Fire Patterns (VG Patterns)

Ventilation-generated fire patterns have been described in the literature as having a slight influence during fuel-controlled conditions, but become the predominant issue with the location and magnitude of damage after the compartment fire is ventilation-controlled (Shanley et al. 1997; NFPA 2014; Carman 2008). First, during fuel-controlled conditions ventilation has been shown to cause the fire plume to lean away from the source of ventilation due to momentum flows from the inflow, thus influencing the truncated cone shape (Shanley, 1997). However, if the fire were to remain in fuel-controlled conditions, it is not expected that this slight change in the damage from the plume would be sufficient to cause an erroneous conclusion as to the cause of the damage.

The more significant issue with ventilation-generated patterns is when the compartment fire is ventilation-controlled. During this phase of the compartment fire, there are adequate UHCs produced, but lack sufficient oxygen for combustion.

The burning during ventilation-controlled conditions is often times detached from a fuel item (i.e. wood chair) and the pyrolyzates (unburned fuel) will burn in locations near ventilation openings and along airflow paths when sufficient oxygen for combustion exists (Custer and Wright 1984; Shanley et al. 1997; Carman 2008; Gorbett et al. 2010). Consequently, temperatures in the upper layer will also vary based on local variations in this combustion. A substantial degree of damage is often times found directly adjacent to or opposite of window and door openings. This type of damage was noted in the USFA study with specificity (Shanley et al. 1997).

Shanley (1997) noted that the effect of ventilation was the one factor least understood and that ventilation-generated patterns were identified to be of great magnitude, sometimes greater than that of the patterns caused by the plume or origin. Their study noted that clean burn areas were observed on wall surfaces under windows that had opened during the fire and that the damage extended from the sill of the window to the floor. Also, their study noted that similar areas of great magnitude of damage occurred around doors, and on walls opposite door openings.

Carman (2008) noted similar areas of damage of great magnitude directly opposite door openings and within the inflow of the air from this door. Several studies noted areas of clean burn and damage of great magnitude occurring around contents and to wall surfaces within this airflow and to wall surfaces directly opposite of the opening during ventilation-controlled conditions (Custer and Wright 1984; Shanley et al. 1997; Carman 2008; Gorbett et al. 2008). Although, Shanley (1997) and Gorbett (2008) do not find this similar effect when performing studies in compartments where the ventilation openings are connected to adjacent compartments, not directly to the exterior. Shanley (1997) reports that a damaged area of great magnitude was identified in the tests done in NIST's Large Fire Research Facility where the ventilation opening to the exterior of the compartment had access to an abundant amount of 'fresh' air. However, this area of damage was not identified in comparison studies performed in acquired structures where the opening was connected to an adjacent compartment within the house. Shanley (1997) contends that the source of available 'fresh' air from adjacent spaces will have a significant influence on whether or not the ventilation-generated patterns are prevalent with such magnitude.

Mealy, Wolfe and Gottuk (2013) identified similar effects near ventilation openings in their compartment fire tests. They identified areas of damage with greater magnitude around the doorway openings. In addition, this study identified that greater damage (clean burn) occurred at the seams between drywall sections within their tests when they were not covered with tape and mud, due to leakage through the unsealed openings. This same damage near the drywall seams was identified in the Claflin study (2013).

Figure 2-13: Ventilation-Generated Fire Pattern near open doorway (fire origin located across room-fire test conducted at EKU by author)

Characteristics of the damage linked with ventilation-generated patterns during ventilation-controlled conditions are large surface areas and increased magnitude of damage, angled lines of demarcation located around the ventilation opening or directly opposite of a door opening. Also, damage may be found near the unsealed seams of drywall sections due to infiltrating air.

2.3.2.4 Suppression Generated Fire Patterns (SG Patterns)

Suppression factors may also impact the visible and measurable damage that investigators use. These factors included the location of water application, duration of fire burning prior to arrival, duration required to extinguish the fire, location of fire department entry, method of extinguishment, use of positive pressure ventilation (i.e. forced convection, mechanical movement of smoke or spreading of contaminants), the change of ventilation upon arrival (breaking windows, opening doors, cutting holes in ceiling), and overhaul after the fire has been extinguished.

No studies have been conducted specifically to evaluate these patterns, however, some characteristics of these patterns have been identified in other fire pattern studies. Shanley (1997) reported that suppression-generated patterns, those caused by water spray from a fire department hose line, were easily identifiable in their test series. The water spray damage was composed of many elongated streaks, less than 1-inch in length, and were grouped and oriented so that they resembled a spray pattern. This study also noted that it was evident that the water did not wash all of the deposited material away from the wall or ceiling surface because "the patterns had a color which was lighter than the surrounding area but not as light as a clean burn or protected area" (Shanley et al. 1997).

Mealy, Wolfe, and Gottuk (2013) identified hose spray from suppression efforts as washing off areas of soot and ash from the gypsum wallboard, leaving behind a white area. These white areas were similar in appearance to clean burn patterns at first glance, but were shown upon closer examination to be differentiated based on smeared, directional appearance with observable water drip marks.

Many of the firefighting factors would not necessarily develop new patterns that have unique characteristics. For example, the location of fire department entry, the use of positive pressure ventilation, and the change of ventilation upon arrival should result in fire patterns that are similar to ventilation-generated fire patterns. The only point of contention then would be the manner in which the ventilation opening was created. Finally, an area that is white in color surrounded by soot areas should not be classified as a clean burn area until closer examination is performed.

2.3.2.5 Alternate Causal Factors

Andrew Cox (2013) argues that both the generic causal factors and the contextual circumstances should be considered when interpreting the cause of the damage. Cox provides an example where using these two concepts demonstrated that a white area on a wall required consideration of the causal factors and contextual circumstances to adequately evaluate the damage. He lists causal factors for this white area of damage as possibly hose stream wash, surface paper burned off leaving a 'clean' noncombustible surface behind, or the wall may have been surfaced differently prior to the fire (i.e. repairs of the drywall performed). He then indicates that the contextual circumstances should also be evaluated, which include a relationship to other artifacts and associated casual factors (proximity to a fuel item), post-flashover conditions, and proximity of damage to a ventilation opening. The changes to the wall surfaces by the owner through repairs and other possible information that may change the overall damage within the compartment need to be addressed.

Drywall repairs, as well as tape and mud between drywall seams or the lack of this material may alter the observations of damage in these areas and will need to be considered. Several researchers have identified significant changes in damage around drywall seams (Claflin 2014; Gorbett et al. 2010; Mealy et al. 2013). If the mud and tape were present to cover the drywall seams, then typically the damage is lesser at this area. However, if the mud and tape are not present and the compartment transitioned to a ventilation-controlled fire, the damage around these sources of ventilation may be significant (Claflin 2014; Mealy et al. 2013).

Figure 2-14: Pre-fire Drywall Repairs Influencing the Post-fire Visible Damage to the Wall (fire origin located along front of chair-fire test conducted at EKU by author)

2.4 Literature regarding the practice of using damage in fire investigations

This section of the literature review focuses on the use of fire patterns and fire pattern generation to identify an area of origin. Since the beginning of fire investigations, the focus on how to determine the area of origin for a fire was to try and use damage to work backwards in an attempt to recreate the development of the fire within the investigator's mind. Many of the early texts discuss this similarly to Rethoret when he states "using the method of tracing the course of the fire and by working backwards, the actual place where the fire originated can usually be determined by the greatest damage" (Rethoret 1945). In essence this shows that fire investigators were trained to identify the greatest area of damage and that this would be the area of origin. However, even the earliest text on fire investigation cautions investigators that ventilation may cause trouble with this process as it will cause greater damage in those areas of better "air currents" (Rethoret 1945). The earliest texts (Rethoret 1945; Kennedy 1962), however, do not offer a process on how to use the data, other than vague descriptions on visibly identifying greater areas of damage and tracing varying char damage.

The first identified process was published in 1955 (Straeter and Crawford 1955). The authors stated that "fire leaves its fingerprints and that each finger of flame leaves its effects, and the study of these effects will help you pick the spot where it burned first" (Straeter and Crawford 1955). To accomplish this goal, the authors suggested that the area of origin could be identified through the use of damage by both (1) retracing the fire's path by the forces bearing on it and (2) retracing or reconstructing the path of the fire by the effects produced. The forces bearing on the fire were identified in this text as (a) combustibles involved, (b) openings and ventilation, (c) winds and drafts, (d) explosions, and (e) variations from normal burning. The most emphasis was placed on combustibles involved and openings and ventilation.

The authors suggested that the investigator could evaluate the items involved and "the differences of flammability of combustibles along the route of travel may explain the route of travel or spread" (Straeter and Crawford 1955). They also discussed that locations and conditions of ventilation openings as functioning in "two different capacities, where the fire could pass to the next room…or it may be a source of incoming air to feed the fire" (Straeter and Crawford 1955). The second way to retrace the path of the fire towards the origin was by the use of the effects produced, which they broke down into evaluating six parts including (a) char, (b) remains and debris, (c) room temperatures, (d) sequence of shorted electric circuits, (e) sequence of sprinkler eruptions, (f) interiors of partitions, and (g) adjoining properties.

The section on char suggested that the investigator go backward from the areas of "little char to deeper char establishing the path of fire clearly" (Straeter and Crawford 1955). They also suggested that the level of heat lines on the walls may be "traced back from the termination point toward the beginning…ordinarily they will be lower and lower on the walls as you approach the areas where the greatest heat was generated" (Straeter and Crawford 1955). This combination of using damage in the context of the fire behavior variables was new to the profession in 1955, but then apparently lost for the next forty years. The authors do not, however, indicate how, provided this information, an investigator arrives at a conclusion.

The next identified process was promulgated by John Kennedy in 1962 and was termed the Pointer or Arrow Theory (Kennedy 1962). The pointer theory was proffered as a "system of determining the point of origin of a fire by tracing its path back to its source…the system is based on the fact that fires normally travel by feeding on flammables. The sides exposed to the direction from which the fire is coming will be more severely burned and charred. This will leave a series of burned studs, which serve as pointers or arrows to trace the fire" (Kennedy 1962). Again, Kennedy makes the argument that the investigator needs to identify the greatest area of damage. Kennedy incorrectly makes the assumption that "in fires involving buildings or other structures where wooden joists or studding are exposed and burning, the application of the fire will usually be constant" (Kennedy 1962).

Kirk was the next to put forward a general process on how to identify the area of origin based on damage. The focus of his process was similar to the others in describing that the area of origin will be located at the greatest area of damage and the investigators should focus on identifying the low burn damage areas and using conical shapes. He encouraged investigators to focus on low burns, because as he says "any low point in a burn should be investigated as a possible origin" (Kirk 1969). However, Kirk also identifies many of the "very common complications" that can arise, which will "distract the investigator from following the fire pattern back to its point of origin" (Kirk 1969). These deviations from 'normal' patterns, as he called them, included areas of open ventilation, secondary ignition of falling material, roof or attic fires, exterior exposure fires, and roof collapse. He succinctly describes his process as "direction of spread of the fire will be noted…it will be upward, partially lateral, rarely downward, but its direction will indicate the general region of origin when properly interpreted. This should and generally is, close to the low point of the burn" (Kirk 1969).

Kennedys (1985) described a first method as "the 'V' pattern method is based on the fact that fire burns upward and outward toward available fuel, leaving a 'V' shaped pattern that can be traced back to its lowest point which would be the area of origin". The only method that appears to be systematized and examples provided was the truncated cone method in conjunction with the heat and flame vector analysis (Kennedy and Kennedy 1985). This method was used to identify each fire pattern within the compartment, ascribe a direction or intensity to that damage, and assign a directional arrow on a diagram to reflect this damage, however, no specific procedural details were provided on how to implement this analysis or how to interpret direction (Kennedy and Kennedy 1985).

In 1985, Cooke and Ide put forward a process termed *radius of error* (Cooke and Ide 1985). Their method encouraged investigators to use fire patterns to arrive at an origin, but upon arriving at their hypothetical area(s) of origin required the investigator to provide some measure of accuracy in the form of a radius of error. Their example is as follows, "if the investigator decides he has located a seat of fire within a radius of error of 1m, he is *certain* that the original seat of fire lays within an area having one metres *[sic]* radius (i.e. within an area of 3.14 square metres *[sic]*)" (Cooke and Ide 1985). Their use of this method was stated to ensure that an investigator would be required to provide an indication of the degree of accuracy, as well as provide an area for excavation. This was the first time that investigators were encouraged to assign some reliability to their origin conclusion, however, the authors failed to provide guidelines on how specifically to arrive at the initial origin hypothesis.

Since 1992, NFPA 921 has established the *de facto* standard of care for the fire investigation profession, yet it lacks specific procedures for origin determination (Gorbett and Chapdelaine 2014). The only procedural aspect that NFPA 921 provides for fire pattern use for origin determination is the heat and flame vector analysis (NFPA 2014). However, no specific details are provided on how to implement this analysis. The scientific method is proclaimed throughout the document as the generic process for investigating a fire, but no specific procedural details are outlined on how to implement it into practice for analyzing fire patterns.

In 1997, a formal heat and flame vector analysis was conducted with three of the USFA fire pattern tests. The results confirmed that the use of this method was appropriate for these three test fires (Shanley et al. 1997). This was the first published work that outlined how to develop a legend and diagram as demonstrative aids for applying the heat and flame vector analysis. It can be argued that this study was the nearest any of the methods have come to being testing for reliability or validity.

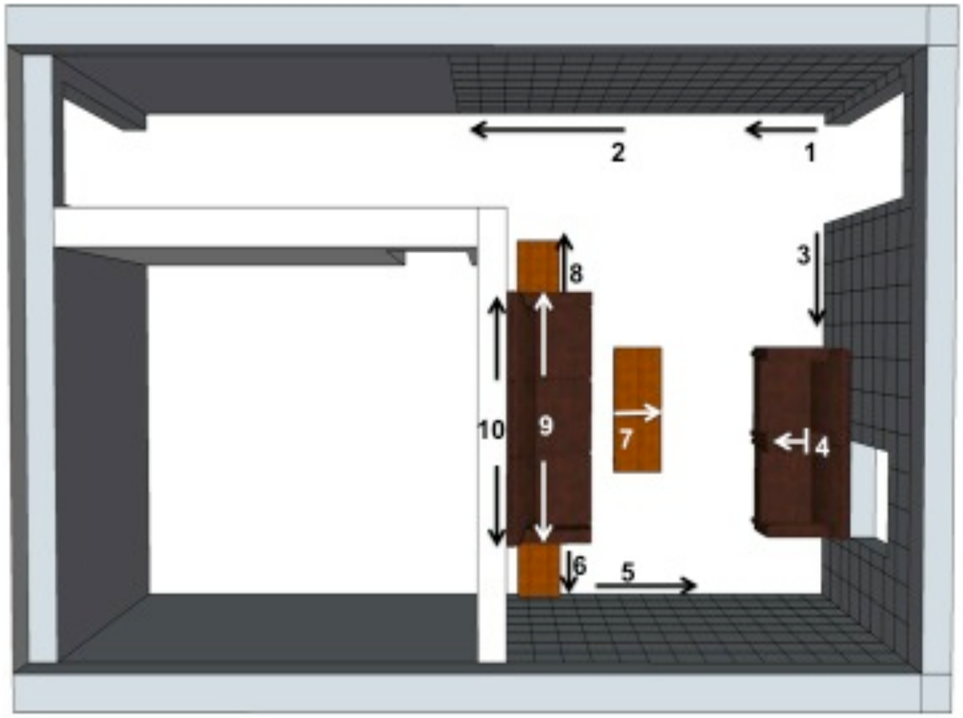

Figure 2-15: Example of a Heat and Flame Vector Analysis Diagram (fire origin located in center of couch-fire test conducted at EKU by author)

Table 2-2: Example of a Heat and Flame Vector Analysis Legend

Vector	Material	Effect	Fire Patterns Analysis
1	Gypsum wallboard	Clean burn	Clean burn extending from doorway 5' into compartment. Indicating intensity near the doorway.
2	Gypsum wallboard	Color change	Increasing line of demarcation moving down hallway. Indicating fire travel from living room down the hallway.
3	Gypsum wallboard	Clean burn	Clean burn extending from doorway to loveseat. Indicating intensity near doorway.
4	PU foam	Loss of mass	Backrest cushion completely consumed, horizontal cushion still present. Near uniform heat from top down, indicating a hot gas layer generated pattern.
5	Gypsum wallboard	Depth of calcination	Deeper calcination measurements in S corner of east wall. Indicating fire travel from S end of room towards N.
6	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
7	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
8	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
9	PU foam / wood	Loss of mass; char	Greater char and loss of mass in center of sofa. Indicating fire travel from sofa.

10	Gypsum wallboard	Clean burn; depth of calcination	Greatest area of clean burn and depth of calcination above and behind center of sofa. Indicating fire travel from sofa.

In 2002, fire pattern analysis was identified as an essential area of research by the National Fire Protection Association's Fire Protection Research Foundation. In their report, authored by its Research Council on Post-Fire Investigation, they recommended, "if patterns are to be used for origin and cause determination, forensic methods to identify the specific source of a pattern need to be developed and rigorously vetted" (NFPA, 2002, p.5).

The first insistence that decision analysis should be considered for fire patterns analysis was in 2010 (Gorbett et al. 2010). The study divided the use of fire patterns into fire effects and fire dynamics attributes, and called for some form of weighting of fire dynamics attributes in the overall decision process. However, the authors did not propose a working prototype.

A survey was conducted to evaluate the proficiency of professional fire investigators at determining the area of origin when provided with photographs and measurable data from a test (Tinsley and Gorbett 2013). The accuracy of the proficiency test was matched with the demographics of 586 professional fire investigators. The test fire used for this survey was setup as a residential living room furnished with a polyurethane foam couch and loveseat, end tables, and a coffee table. The walls and ceiling were lined with gypsum wallboard. The fire burned for approximately two minutes post-flashover.

The participants were provided a diagram of the room and photographs of the contents, walls, and ceiling. An approximate 2-square foot ($0.19m^2$) grid was established and the participants were asked to select the grid space that most represented their area of origin. Next, the participants were provided with depth of char measurements for all content items and depth of calcination measurements for all of the walls for the same compartment fire and were asked to re-examine the photographs and select an area of origin again. The study concluded that 73.8% without measurable data and 77.7% with measurable data accurately determined the area of origin. Thus, the total percentage of participants choosing the correct area increased 3.9% with the inclusion of measurable data as part of the given. These results were found to be statistically significant using a chi square distribution yielding a p-value of 0.006.

In 2013, Andrew Cox published an article proposing a new methodology for the assessment and interpretation of compartment fire damage through the use of what he termed the origin matrix (Cox 2013). Essentially this work establishes a rudimentary decision matrix that uses pre-flashover and varying durations of post-flashover as the primary consideration in identifying the location and magnitude of damage within the compartment. The central theme is that the investigator can section off a room and can use the location of ventilation openings as a predictor of the location and magnitude of damage based on the location of this ventilation and the predicted airflow from these openings.

Cox discussed the importance of separating data and the interpretation of that data when discussing this new method. He contends that damage should just be viewed as data, and the investigator "must resist the temptation to interpret the meaning of individual fire effects and fire patterns in isolation" (Cox 2013). The origin matrix provides the user a diagram of the compartment of interest, where the user is to shade in those portions of the diagram where damage is identified and then this damage is to be compared to expected damage based on the predicted damage from the ventilation openings. Cox provided a process for better interpreting the compartment fire dynamics that is still under development and has not undergone a major field test for user application.

2.5 Discussion and Significant Findings from the Literature Review

A summary of the findings from the literature review and recommendations based on this review will be provided within this section. The literature on using fire patterns to determine an area of origin should be classified into four areas that will assist in guiding future research, including:

(1) Assessing the varying Degrees of Fire Damage (DOFD) along the surfaces of the compartment and contents (i.e. fire effects);
(2) Identifying clusters and trends of damage (i.e. fire patterns);
(3) Interpreting the causal factors for the generation of the fire patterns; and,
(4) Identifying processes of using fire patterns in determining an area of origin.

2.5.1 Assessing the Varying Degrees of Fire Damage (DOFD)–Fire Effects

Many of the early and current researchers assumed that every investigator was able to visibly assess varying degrees of damage equally without processes (Shanley et al. 1997; NFPA 2014; Gorbett et al. 2010). As shown in the literature search, no system exists and therefore this assumption is unwarranted by previous researchers (Carman 2008; Tinsley and Gorbett 2013; Gorbett et al. 2014). Because the varying DOFD serves as the foundation for all later interpretations, ultimately leading to an origin determination, more research is needed to either demonstrate that investigators reliably identify varying DOFD or the industry needs processes that are shown to be reliable and valid (Gorbett and Chapedelaine 2014).

2.5.1.1 Visible and Measurable Observations of Char

Currently, investigators have no reliable method for identifying varying DOFD for charring. One method was suggested, but was never fully conceived or put into practice (Keith and Smith 1984). This method or a similar method should be further explored using the work done for gypsum wallboard (Gorbett et al. 2014). The literature appears to identify that fire investigators can take depth measurements of char for similar types of wood to identify relative degrees of fire damage and that this may assist in identifying varying DOFD, but they should not assign duration of exposure to those measurements unless the conditions of the samples can meet those specifically expressed in Babrauskas's (2005) work.

2.5.1.2 Visible and Measurable Observations of Calcination

A visible degree of fire damage scale (DOFD) was developed for gypsum wallboard and was shown to decrease variability in novices ranking varying degrees of fire damage across a wall surface (Gorbett et al. 2014). More work is required to further examine these results. Several studies have shown that the depth of calcination reliably indicates intensity and duration of heat exposure. A standardized depth tool needs to be implemented to decrease error, similar to the one developed by Barnott, Hardman, and Hoff (2013). A new method of using digital image analysis may also work in increasing the objectivity of identifying varying DOFD (Riahi 2013). Most of the studies conducted on calcination are limited in their examination of gypsum wallboard variations. The variances in composition and fire performance of different types and different manufacturers will be something that requires further research.

2.5.2 Identifying Fire Patterns

No literature exists that defines methods on how to identify a fire pattern from a cluster of damage. It is important for reliability and validity that the industry develop processes to assist investigators to objectively identify fire patterns.

The current definition for fire patterns is "the visible or measurable physical changes, or identifiable shapes, formed by a fire effect or group of fire effects" (NFPA 2014). This definition is insufficient compared to how the profession currently uses the term. A better definition is warranted for this term.

As the definition from the term fire pattern has evolved and will continue to evolve, it is important to define what a pattern is first. The most common definition of a pattern is "something that happens in a regular and repeated way, combination of qualities forming consistent or characteristic arrangement, and frequent or widespread incidence" ("Pattern" n.d.). The fundamental items within the definition that may assist in better defining the term *fire pattern* is that patterns are something that happens in regular and repeated ways with characteristic features.

Combining the definition of *pattern* with the current definition of *fire patterns* provides a better definition. The proposed definition for fire patterns is

> "a distinct area of damage or cluster of fire effects with identifiable and related lines of demarcation that share common damage characteristics, such as type, magnitude, direction, and proximity (e.g. location and elevation)".

The elements of the fire pattern definition are further explained here:

1. "distinct area of damage or cluster of fire effects" – the area of damage must be clearly distinguishable from other areas of damage through the identification of line(s) of demarcation. Other areas of damage can surround the pattern, but the pattern must have characteristics that allow the limits of it to be individually identified.
2. "identifiable and related lines of demarcation" – it is important that the lines of demarcation are objectively verifiable by all experts and that a pattern is something that can be objectively identified without interpretation. The related lines of demarcation are ensuring that the area being called a pattern have associated boundaries or lines of demarcation. The term 'related' also is included to permit the linkage of the lines of demarcation with

progressively increasing or decreasing degrees of damage, such as flow of a hot gas into/out of a compartment.

3. "share common damage characteristics" – for the damage to transition from simply random areas of damage to being classified as a pattern requires that the damages are clustered near to each other and that the characteristics of the damage are similar.
4. The characteristics that are proposed here include the "*type, magnitude, direction, and proximity (e.g. location and elevation)*". Magnitude refers to the degree of damage to the material. A pattern requires that the degree of damage between varying materials and along the same material reflect a similar intensity / duration of exposure to the byproducts of combustion. As mentioned before, if the magnitude of damage is changing, but the lines of demarcation are related, then a pattern may still exist. A pattern may encompass the varying DOFD areas as long as the line of demarcation are linked by direction. Proximity requires that the varying fire effects be within the same vicinity to each other. Location and elevation are essentially further describing proximity. Finally, 'type of damage' indicates the physical or chemical changes to the material, such as penetration, flaking, deposition, consumption, and other material decomposition fire effects.

Processes that identify thresholds needed for fire patterns to be identified can be better defined through experimental work or pattern recognition studies.

2.5.3 Fire Pattern Generation

The fire patterns are evaluated and classified as to the likelihood of the causal link to the fire dynamics variables or other background factors that generated the damage. NFPA 921 (2014) refers to this as fire pattern generation and provides a list of them including plume-generated, ventilation-generated, hot gas layer-generated, and suppression-generated. Attributing a fundamental interpretation to an observation, specifically one that ties the underlying physics to an observation, is a major key to accurately determining the true fire scenario and area of origin. Ultimately, the locations of damage and fire patterns are compared to the causal factors from the physics of the fire, alternative causes, and background information.

2.5.3.1 Plume-Generated (PG) Fire Patterns

The characteristics distilled from the literature are that plume-generated patterns have areas of greater magnitude of damage in relation to the surrounding areas and because of this, the lines of demarcation between these areas are described as clear or sharp. Also, the lines of demarcation are not parallel to the floor, but are at an angle representing the buoyant flow, usually with characteristic geometric shapes. The fire pattern studies revealed that specific damage cues identified during fuel-controlled conditions were not as prevalent during ventilation-controlled conditions.

The damage cues evaluated for plume-generated damage included:

- Cue 1-loss of mass to fuel is consistent with damage to affected surface.
- Cue 2-increased magnitude of damage near the fuel item.
- Cue 3-elevation of the line of demarcation is consistent with the height of the fuel item.
- Cue 4-width of base of damage is approximately the width of the fuel item and not greater than two times the width of the fuel item.
- Cue 5-lines of demarcation are angled emanating from the fuel item.
- Cue 6-sharp/distinct lines of demarcation near or appear to be emanating from the fuel item.
- Cue 7-conical shape.

The following statistics were accumulated while performing the literature review and summarized here for PG fire patterns. The statistics can be found in the Excel Spreadsheet associated with this review paper. The fuel-controlled conditions had consistently higher probabilities in positively identifying each cue as compared to ventilation-controlled conditions. In fuel-controlled conditions, cues 2-4 were positively identified in 92% of the studies (23/25), cues 1 and 5 were positively identified in 88% of the studies (22/25), cue 6 was positively identified in 84% of the studies (21/25), and cue 7 was identified in only 68% of the studies (17/25). In ventilation-controlled conditions, cue 1 was the most positively identified in 87% of the studies (39/45), cues 2-5 were identified in 76% of the studies (34/45), cue 6 was identified in 62% of the studies (28/45), and cue 7 was only identified in 42% of the studies (19/45).

2.5.3.2 Upper Layer-Generated (ULG) Fire Patterns

The characteristics distilled from the literature are that the ULG patterns will have level lines of demarcation with relatively uniform magnitude of damage, unless the upper layer is flowing out of a compartment and if so the lines of demarcation will be angled towards the opening.

The fire pattern studies revealed that the upper layer damage is very difficult to identify after the fire has transitioned into ventilation-controlled conditions. The presence of a soffit and the size of an opening influences the depth of the damage within the compartment, however, as the compartment nears flashover damage begins to occur at lower elevations on all surfaces. This damage begins to obscure some of the earlier lines of demarcation from the upper layer. The damage cues evaluated for upper layer-generated damage included:

- Cue 1-damage high in elevation on wall surfaces.
- Cue 2-uniform magnitude of damage.
- Cue 3- increasing lines of demarcation moving out of vent openings.
- Cue 4- level lines of demarcation along all wall surfaces.

The following statistics were accumulated while performing the literature review and summarized here for ULG fire patterns. The statistics can be found in the Excel Spreadsheet associated with this review paper. The ventilation-controlled conditions did not result in any upper layer damage that was discernable, therefore it will not be considered here. In fuel-controlled conditions, cues 1 and 2 were the most positively identified in 80% of the studies (20/25), cue 3 was identified in 60% of the studies (15/25), and cue 4 was only identified in 48% of the studies (12/25). Given these findings, damage cues 1, 2, and 3 are used as the most accurate damage cues for classifying a fire pattern generated by upper layer.

2.5.3.3 Ventilation-Generated (VG) Fire Patterns

Characteristics of the damage linked with ventilation-generated patterns during ventilation-controlled conditions are large surface areas of damage, increased magnitude of damage, damage found near unsealed drywall seams, and angled lines of demarcation located around the ventilation opening or directly opposite of a door opening.

The fire pattern studies revealed that ventilation rarely causes any damage of significance during fuel-controlled conditions. However, ventilation becomes one of the more prominent influences of damage when the compartment has transitioned into ventilation-controlled conditions. The presence of a ventilation opening is necessary. Door openings to the exterior were identified as being the most influential to damage. The damage cues evaluated for ventilation-generated damage included:

- Cue 1- increased area and magnitude of damage within the airflow from the opening.
- Cue 2-increased area and magnitude of damage across from the opening.
- Cue 3-increased magnitude of damage around opening within 2 times the opening width ($2w_v$).
- Cue 4-lines of demarcation are angled emanating from the ventilation opening.
- Cue 5-increased area and magnitude of damage under the window.
- Cue 6-increased area and magnitude of damage around gypsum wallboard seams.

The following statistics were accumulated while performing the literature review and summarized here for VG fire patterns. The statistics can be found in the Excel Spreadsheet associated with this review paper. The fuel-controlled conditions did not have any damage associated with ventilation openings, therefore it will not be considered here. In ventilation-controlled conditions, cue 1 was the most positively identified in 82% of the studies (37/45), cue 2 was identified in 73% of the studies (33/45), cue 4 was identified in 64% of the studies (29/45), cue 6 was identified in 62% of the studies (28/45), cue 3 was identified in 53% of the studies (24/45), and cue 5 was only identified in 11% of the studies. Given these findings, damage cues 1, 2, and 4 are used as the most accurate damage cues for classifying a fire pattern generated by ventilation.

2.5.3.4 Suppression-Generated (SG) Fire Patterns

Many of the suppression factors would not necessarily develop new patterns that have unique characteristics. For example, the location of fire department entry, the use of positive pressure ventilation, and the change of ventilation upon arrival should result in fire patterns that are similar to ventilation-generated fire patterns. The only point of contention then would be the manner and reason in which the ventilation opening was created. Finally, an area that is white in color surrounded by soot areas should not be classified as a clean burn area until closer examination is performed.

2.5.3.4 Undetermined-Generated (UKG) Fire Patterns

If the fire pattern generation cannot be conclusively determined, then the fire pattern generation is noted as undetermined (UKG).

2.5.4 Identifying Processes of Using Fire Patterns in Determining an Area of Origin

In the face of non-systematized approaches to solving complex problems, the current state of fire investigation, many other professions have turned to decision support frameworks, tools or methods. As used here, decision frameworks, tools or methods encompass any mechanism used to support the systematic identification and assessment of information deemed important to a decision, ranging from checklists to structured problem-diagnostic tools such as fault trees, event trees or decision trees, to computationally supported decision analysis tools. Decision support frameworks are derived from the field of decision analysis, as well as from uncertainty analysis and risk analysis.

Decision analysis has its roots in operations research, where it emerged from a desire to better understand and address decision-making under uncertainty, becoming viewed as a unique area of study in the 1960s (Howard 1966; Raiffa 1968). A fundamental principle of decision analysis is that people do not always have all the data or information needed to make a good decision. In addition, they may not know where or how to obtain additional information, or how to judge the value of the information in the context of the overall decision. As these problems began to be studied, approaches were developed to help individuals and organizations identify the components of a good decision, how to structure the decision problem, and how to treat the associated uncertainty (Clemen and Reilly 2001; Donegan 2008; Kahneman and Tversky 1974; Kleindorfer et al. 1993; Morgan and Henrion 1990; Von Winterfeldt and Edwards 1986).

Key aspects of a decision support framework include identification of decision objectives, attributes (criteria) which are important to the decision problem, and the weighting (importance) of the attributes to the decision given the uncertainty and variability in the data and relationship between the attributes. Once these parameters are identified and organized, various techniques can be applied to facilitate the collection of critical information, analysis of the data, and facilitation of a decision.

This type of structured approach to reaching better decisions has been applied in various fields, from business and economic decisions (Clemen and Reilly 2001), to building and fire safety analysis and regulation (Donegan 2008; Meacham 2000), diagnostic support within the psychological, psychiatric, and medical professions (Boorse 1976; DSM-IV-TR 2000), failure analysis (Benner 1975; Ericson 1999; Vesely 2002) and forensic analysis (Taroni et al. 2005; Morvan 2007; Jarman et al. 2008), including with respect to fire investigation (Biedermann et al. 2004).

2.6 Conclusions of Literature Review

The literature review of fire pattern usage in the fire investigation profession illustrates several gaps with the overall process of using damage to determine an area of origin. First, a poor assumption by many of the fire investigation guides, textbooks, and research was that every investigator is able to visibly assess varying DOFD equally (Shanley et al. 1997; NFPA 921 2014; Gorbett et al. 2010). However, this has not been demonstrated through proficiency testing done to determine the area of origin based on visible observations (Carman 2008; Tinsley and Gorbett 2013). Several recent studies have provided processes to assist in the objective identification of the varying degrees of damage, including a degree of fire damage scale for visible damage (Gorbett et al. 2013), a standardized depth measurement system (Mealy et al. 2013), and the use of digital image analysis (Riahi 2013). More validity and reliability studies are required for these methods.

Currently, no systematic method exists for fire investigators to identify a fire pattern. Developing a process for the objective identification of areas requiring further attention during fire investigation that is universally accepted by the community is recommended to increase the reliability and accuracy of fire origin determinations.

The only process for fire pattern analysis discussed in the literature is the use of a heat and flame vector analysis (NFPA 921 2014; Shanley et al. 1997). Many of the studies contend that this process assists investigators in determining the correct area of origin (Shanley et al. 1997; Gorbett et al. 2010). However, no formal procedure has been developed, including: how to determine a direction, how to incorporate compartment fire dynamics into the process, and how to make an area of origin conclusion based on the results. Furthermore, this process has not been widely tested for reliability or validity.

When lacking a systematic approach to solving complex problems, many professions have turned to decision support frameworks, tools or methods, the intent of which are to guide the decision by asking questions and helping to assess the weight or importance of variables. It is suggested from this literature review that the overall reasoning process for evaluating fire damage for determining an area of origin consists of the following seven steps (Gorbett et al. 2015b):

(1) Identifying the value in further analysis of a surface or compartment;
(2) Identification of the varying degrees of fire damage (DOFD) along the surfaces of the compartment and contents;
(3) Identifying clusters and trends of damage (fire patterns);
(4) Interpreting the causal factors for the generation of the fire patterns;

(5) Developing area(s) of origin hypotheses;
(6) Testing the hypothetical area(s) of origin; and,
(7) Selecting a final area of origin hypothesis.

Each of the seven steps will have a process or multiple processes that assist in moving the decision maker through the overall process of determining an area of origin. The profession requires new research to span the gaps identified within each sub process. All processes used for origin determination should undergo reliability and validity testing (Gorbett et al. 2015b). Standardized proficiency testing should be developed for each process developed and all users of these processes should be tested for proficiency.

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3.0 Process of Origin Determination (POD)

The overall reasoning process for evaluating fire damage for determining an area of origin consists of the following seven steps:

(1) Identifying the value in further analysis of a surface or compartment,
(2) Identification of the varying degrees of fire damage (DOFD) along the surfaces of the compartment and contents,
(3) Identifying clusters and trends of damage (fire patterns),
(4) Interpreting the causal factors for the generation of the fire patterns,
(5) Developing area(s) of origin hypotheses,
(6) Testing the hypothetical area(s) of origin, and
(7) Selecting a final area of origin hypothesis.

To properly address each step, a decomposition of the fundamental questions was conducted, in which the Process of Origin Determination (POD) was developed. A simplified decision-tree was used for each step to identify what decisions are needed to advance through the POD. The questions permit the systematic outline of the subprocesses identified for each step.

The goal of this chapter is to describe the POD (a decision support framework) and why it assists fire investigators in arriving at a more supportable outcome for origin determination. The ultimate outcome of the POD is to have a methodology in place that allows investigators to evaluate the damage with a better understanding of the major influences of fire dynamics. Developing the POD required that subprocesses also be established that were objective and reproducible. The subprocesses used within this research were chosen because of their current use within the profession or developed specific for this dissertation. Many of these subprocesses may change when newer technology permits different avenues for collecting or visualizing data. The POD was developed with this in mind. It is expected that when newer technology becomes available and has been shown to reliably provide data that the POD will be able to integrate these newer subprocesses to still assist the decision maker in concluding a more supportable origin determination. For this reason, the discussion in Chapter 3 begins with a basic overview of the POD that illustrates the necessary components for each step regardless of the subprocess used, and then describes the specific subprocesses used within this research study. The subprocesses and many of their results have been clearly described in the appendices and will be referenced to throughout this chapter.

The framework is structured as a sequential decision process where each answer forwards the decision-maker (DM) to the next step within the process. The seven steps of the process listed above serve as the header for each series of questions and the results for each step provide direction to the DM on what next step or conclusion that can be drawn. A word with a bar above it indicates not or negation. A circle with a number inside indicates that the decision maker should move to the next numbered step within the process.

3.1 Step 1 – Value

The first step when evaluating fire damage is to determine if there is any value in analyzing the evidence further. The value question serves as a 'go' or 'no go' type of decision for further analyzing a surface or compartment (Figure 3-1). This question is equivalent to the 'defining the problem' step of the scientific method.

The value question is posed to every lining surface (e.g. walls, partitions, floors, ceilings) and content surfaces (e.g. furniture, appliances) within the compartment, as well as the compartment as a whole. The first decision to be made in evaluating the value is to ask the simple question "is there thermal damage?". A surface exhibits thermal damage when visible or measurable physical or chemical changes occur due to the exposure to the byproducts of combustion. If the answer to the damage question is 'no' for a given surface, then that surface should not be considered near the area of origin. If the entire compartment is evaluated and there is no damage, then that room should not be considered as the area of origin. The phrase 'area of origin' is used many times throughout this work despite the fact that the origin should be considered a volume within the compartment. As such, throughout this chapter damage to a surface is referred to as being considered the area of origin or not, when in fact it is actually only evidence of the area of origin. If the answer to the thermal damage question is 'yes' for a given surface, then that surface is further evaluated through step 2. The guiding questions for this step have been summarized in Table 3-1.

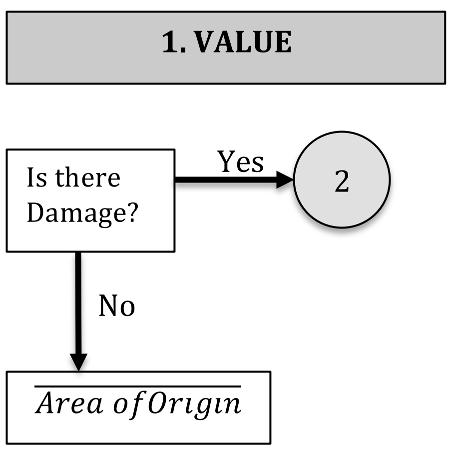

Figure 3-1: Identifying the value of the damage for further analysis

Table 3-1: Step 1 Questions

Question 1: Is there damage? -To each surface exposed. Content, walls, and ceiling
IF yes, then continue with the process (Proceed to Step 2) **IF no, then this damage is not the area of origin (End Process)**

3.1.1 Value

As the simulations and physical experiments consisted of a single compartment, wall and ceiling surfaces had varying levels of thermal damage and were therefore considered to have value. Each wall and ceiling surface was evaluated through the POD for this work. Content surfaces were not evaluated within this work.

3.2 Step 2 – Identifying Varying DOFD

The second step is to further examine the surfaces that exhibited damage identified in step one. The location, magnitude, and boundaries of damaged areas are identified in this step. Several recent studies have provided subprocesses to assist in the objective identification of the varying degrees of damage, including a DOFD scale for visible damage (Gorbett, et. al, 2014), a standardize depth measurement system (Mealy, et. al, 2013), and the use of digital image analysis (Riahi, 2012; Riahi & Beyler, 2011; Riahi, et. al, 2013). Regardless of the subprocess used by the investigator to identify varying DOFD along surfaces, each surface would then be processed through step 3 of the POD (Figure 3-2). This is an area where technology and new processes should be developed to better standardize objective collection of data for use within the POD. In relation to the scientific method, this step corresponds to the 'collect data' step.

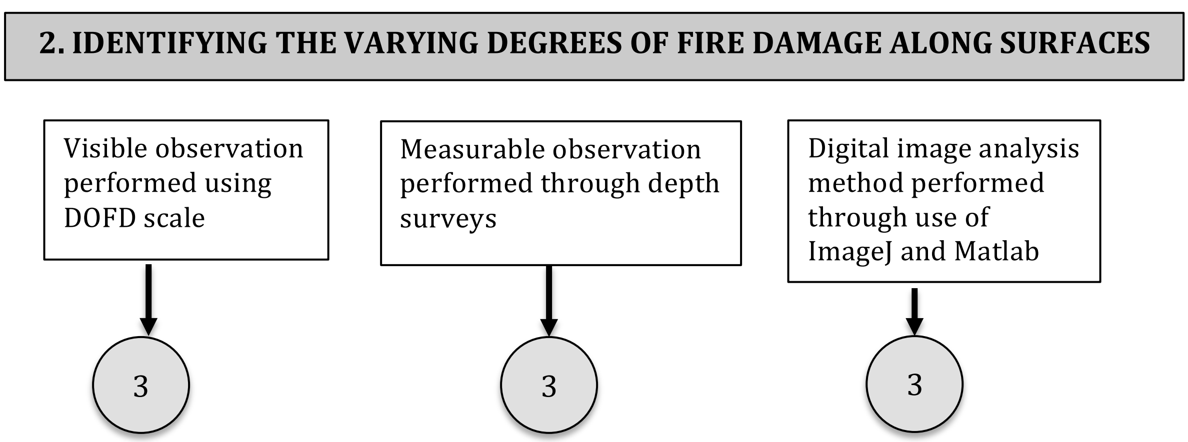

Figure 3-2: Data Collection of the Degree of Fire Damage (DOFD) along surfaces

3.2.1 DOFD Identification

In this dissertation research, predicted damage through the use of FDS numerical simulations were used to develop varying DOFD for the simulations, while the visible damage indicators identified in Appendix B were used for the physical experiments.

3.3 Step 3 – Identifying Fire Patterns

The third step requires a comparative analysis of the data collected from step 2. The purpose of this step is to objectively identify the trends with those areas of damage within the compartment. Ultimately each surface that exhibits a cluster of damage will be ascribed as a single pattern or grouped with other damage that has been shown to extend along other surfaces as a pattern. Thus, providing the decision maker with a discrete number of patterns that must be analyzed through step four of the POD. When a trend is identified along a surface, then the line(s) of demarcation that bounds this area of damage should be clearly identified, the cluster of damage identified as a fire pattern, and a number, described below, assigned to this fire pattern. In the event that the damaged surface does not have a trend or identifiable pattern, then the surface as a whole is identified as a fire pattern and a number assigned. In relation to the scientific method, this step corresponds to the 'analyze data' step.

As a way to decompose the principal theory behind identifying fire patterns, a refined definition of fire patterns was introduced in chapter 2 through a brief introduction of the types of trends evaluated and the general characteristics associated with the identification of fire patterns. The refined definition for fire patterns is *"A distinct area of damage or cluster of fire effects with identifiable and related lines of demarcation that share common damage characteristics, such as type, magnitude, direction, and proximity (e.g. location and elevation)".* An influence diagram for fire pattern identification can be found in figure 3-3. The decision tree that should be considered when evaluating fire damage for trends is found in Figure 3-4.

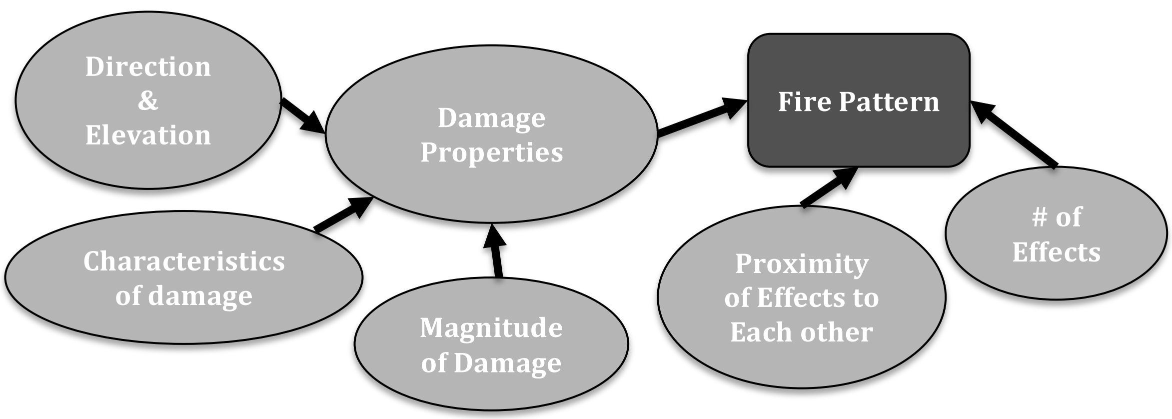

Figure 3-3: Influence Diagram for Fire Pattern Identification

3. IDENTIFYING CLUSTERS AND TRENDS OF DAMAGE (FIRE PATTERNS)

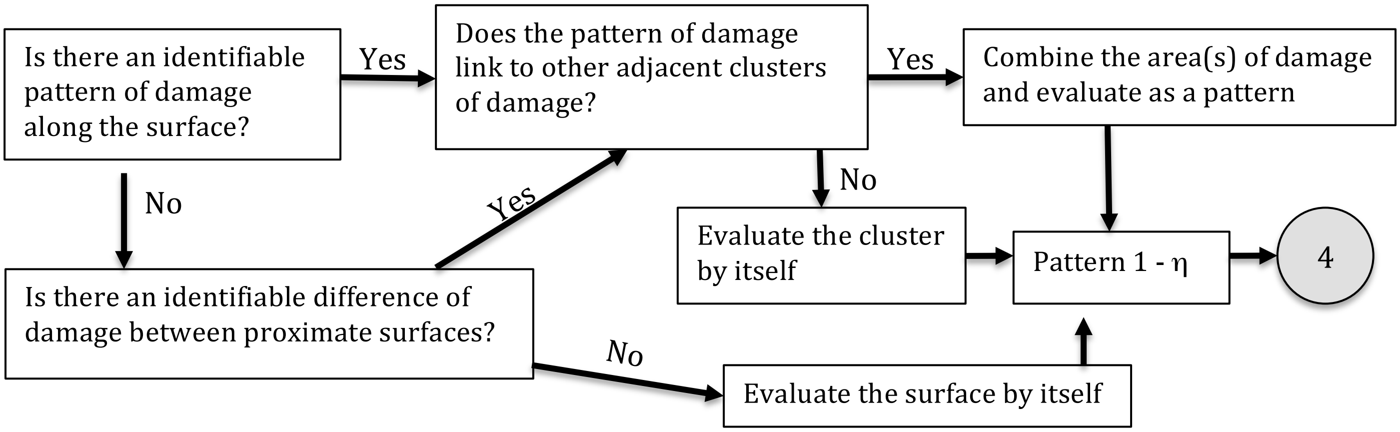

Figure 3-4: Identifying trends or patterns with the damage

The assessment of the varying DOFD along the surface will assist in establishing fire patterns along the single surface. This may be accomplished through comparison of the magnitude of damage to the location and proximity of damage along the surface. These clusters of damage should provide the analyst with a comparative assessment of the surface, which may result in identifying trends with the damage including quadrants or halves (top/bottom, right/left) of the surface exhibiting greater damage. Also, characteristics of the lines of demarcation should be evaluated for trends (e.g. changes in elevation). The identified trend for a single surface is then compared against adjacent surfaces. If there is too much damage along a single surface to identify any trends or varying DOFD, then this surface should be further evaluated against adjacent surfaces to establish any trends between like surfaces (Figure 3-4). If multiple surfaces are within close proximity to each other and have similar damage trends, then it is likely that those areas of damage were caused by the same fire dynamic variables.

The location, magnitude, and damage trends along content surfaces, wall surfaces, and structural members should be compared to each other to identify any potential relationship. Questions that should be analyzed when evaluating a single surface or multiple surfaces can be found in Table 3-2. In the event that there are larger trends with the damage along multiple surfaces, this grouping of damage will be considered as a fire pattern. In the event that there are not larger trends with an area of damage, then this area of damage by itself will also be considered a fire pattern. The assigning of areas of damage to fire patterns streamlines the remainder of the POD.

Damage trends should be identified for like materials (i.e. wall surfaces should be compared, content surfaces of like materials should be compared). This will help identify the relatively greater area(s) of damage within the compartment. For example, a wall surface should be compared to the remaining three walls of the compartment to obtain a general idea of which wall surface received the greater damage. Likewise, contents constructed of like materials (e.g. wood end tables) should be evaluated for relative DOFD within a compartment. Unlike materials should not be compared, due to the different DOFD that may occur from varying heat fluxes. For example, a wicker basket should not be compared to a wooden end table due to the significant differences in DOFD caused by various heat exposures.

Next, trends should be evaluated with the characteristics of the line(s) of demarcation along the surfaces. The lines of demarcation should be evaluated for trends related to extension of damage across surfaces, uniformity, directionality, and elevation changes. The characteristics associated with lines of demarcation should be specifically evaluated for changes in the elevation of damage along all three axes (Figure 3-5). The elevation and varying magnitude of damage associated with the lines of demarcation need to be documented. Traditionally, the changes in elevation and lateral positions have been used as indicative of fire spread or travel and/or the lack of travel (lines of demarcation uniform in elevation).

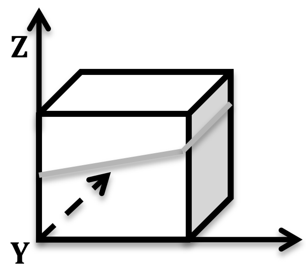

Figure 3-5: Three-Axes to be Evaluated for Changes in Lines of Demarcation

Table 3-2: Step 3 Questions

Question 2: Is there a cluster(s) of damage or trends with the damage along the single surface? -To each surface exposed. Content, walls, and floor
-To each surface exposed. Each content, wall, and ceiling. Identify the following trends for each surface: - More damage on the left or right, - More damage to the top or bottom, - More damage to the front or back, - Which quadrant of this surface exhibits the greatest damage? - Which half (top/bottom & left/right) of this surface exhibits the greatest damage?
IF yes, note the trend and proceed to Step 3. **IF no, then proceed to Step 3.**
Question 3: Is the area of damage connected to other adjacent area(s) of damage? - Location and Proximity - Are the area(s) of damage located near to each other? - Do the area(s) of damage share similar elevations and locations? - Contrast - Similar color? - Similar texture? - Similar Loss of Mass? - Magnitude of damage - Similar type of fire effect?

- Similar heat flux, temperature, or duration of exposure?
- Comparable materials?

- Connecting lines of demarcation to other items within close proximity:
    - Does the damage indicate similar or opposite direction?
    - Does the damage appear to extend to another surface?
    - Does the damage match in direction of magnitude, including the analysis of all 3-axes?
    - Does the elevation of damage connect to those identified on surfaces adjacent to the surface being examined?

IF yes, then combine area(s) of damage as one fire pattern throughout the rest of the process (Proceed to Step 4)
IF no, then evaluate the cluster by itself as a fire pattern throughout the rest of the process. (Proceed to Step 4)

3.3.1 Fire Pattern Identification

The subprocess used within this dissertation research study for identifying fire patterns is outlined in three steps (1) lines of demarcation were captured through contour plots developed for each surface based on the gradient field for the DOFD collected from step 2, (2) vectors associated with this gradient field were calculated and overlaid on the contour plot of the gradients, and (3) a successive evaluation of the varying gradients was used to identify the fire patterns. Each fire pattern was then provided a number for classification purposes to be used throughout the remainder of the process. A worked example of this subprocess is shown in Appendix C. The following 6 steps were used to find these areas and trends:

1. Perform gradient calculations for the DOFD matrices (collected from step 2) for each surface.
2. Plot the gradient changes as contours.
3. Use a quiver plot to illustrate the gradient changes as vectors overlaid on the contour plot. The vectors illustrate the direction from lesser to greater damage (smaller to larger numbers) and the length of the arrow depicts the magnitude associated with that change.
4. To identify areas of greater damage and the trends associated with these areas, a threshold for the gradients was greater than 1.0 utilized.
5. Each surface was evaluated independently for areas of greater damage and their respective trends.
6. Each area of damage identified was catalogued as a fire pattern and assessed through step four in the POD.

3.4 Step 4 – Fire Pattern Generation

This step focuses on assigning causal factors for the fire pattern(s) identified in step 3. The fire patterns are evaluated and classified as to the likelihood of the causal link to the fire dynamic variables or other causal factors that generated the damage. NFPA 921 (2014) refers to this as fire pattern generation and provides a list of them including plume-generated (PG), ventilation-generated (VG), upper layer-generated (ULG), and suppression-generated (SG). How to address a fire pattern that has characteristics consistent with multiple causes is not addressed in NFPA 921. In this work, the lack of one generation being prominantly identified requires that the fire pattern generation be identified as undetermined-generation (UKG).

Attributing a fundamental interpretation to an observation, specifically one that ties the underlying physics to an observation, is a major key to accurately determining the fire scenario and area of origin. Ultimately, the locations of damage and fire patterns are compared to the causal factors from the physics of the fire, alternative causes, and background information. The attributes that are associated with assisting the DM in this step will be the coordination of various information including, the compartment layout, ventilation openings, fuel items, damage characteristics, and other potential causes of damage.

One difficult aspect in the evaluation of fire pattern generation is the delineation between those factors that influence the physics and those factors that influence the observations that assist the DM in making a determination regarding the causation of the fire pattern. Further complicating the decision is that forensic science is based on the evaluation of evidence after an event, which means that fire investigators use discrete observations of damage to assist in their hypotheses of the physics. This seems contradictory to the natural order of determining the factors of influence. The requirement to identify the physics based on discrete observations appears initially to be a restrictive factor to the DM; however, if this information is processed correctly the analysis may be strengthened.

For example, if a prediction of the burning regime within a compartment (i.e. fuel-controlled or ventilation-controlled) were required, then the DM could evaluate the factors influencing the physics (e.g. HRR of fuel(s), compartment volume, ventilation) to arrive at a probability that the fire will transition from fuel-controlled to ventilation-controlled. The probability associated with this analysis will be dependent on the methodology used by the DM (i.e. empirical data, computational fluid dynamics) and may have significant uncertainty associated with it, as it would be based on empirical data and mathematical expressions from test data. Often times, this is the role of a design engineer, where he must make a decision or prediction solely on this information (prior). The fire investigator, on the other hand, has additional observations and data that exist post-fire that can be used to update the uncertainty of the initial probability regarding the burning regime decision (posterior). In statistical inference, the updating of a degree of belief based on collected evidence is most commonly associated with Bayesian inference.

A decision tree outlining the general subprocess for identifying fire pattern generation can be found in Figure 3-6. Some of the questions that need to be evaluated by the decision maker is found in Table 3-3. In relationship to the scientific method, this step corresponds to the 'analyze data' step.

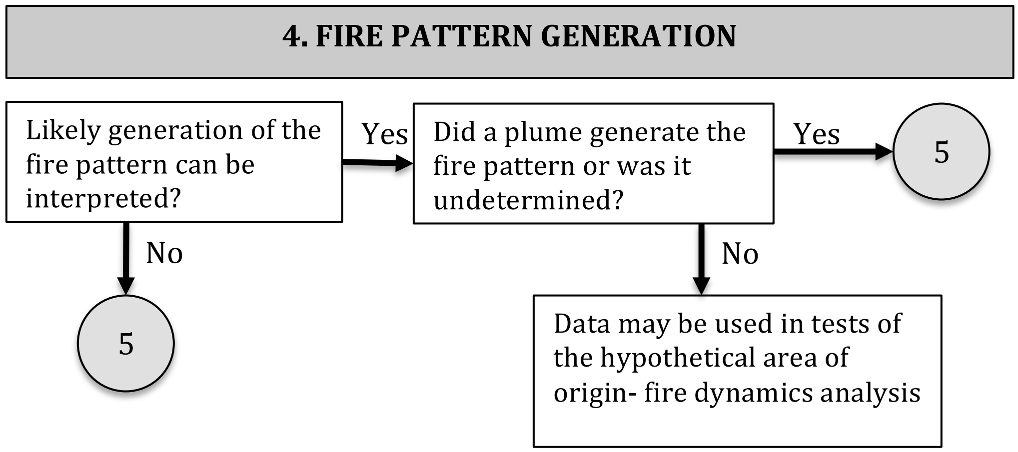

Figure 3-6: Interpretation of causal factors for fire patterns

Table 3-3: Step 4 Questions

Question 6: What caused the fire pattern? What attributes of the damage assist in determining the cause? - Lines of demarcation - Type of fire effects - Magnitude of fire effects - Elevation changes What attributes of the environment assist in determining the cause? - Burning regime - Ventilation characteristics - Fuel characteristics - Suppression characteristics - Geometry and layout of the compartment Causal link between damage characteristics and the interpretation of the damage - Likelihood of the damage as it relates to being generated by a flame plume, upper layer, suppression, ventilation, other causes, or it cannot be determined.
IF the cause can be conclusively determined, then note and proceed to step 5. **IF the cause cannot be conclusively determined, then note the damage as undetermined generation and proceed to Step 5.**

3.4.1 Bayesian Networks Developed

Decision tools were developed in the form of Bayesian Networks (BNs) to assist the decision maker in determination of the generation of damage. Qualitative and quantitative attributes were used to develop these BNs. The attributes that were used within the development of the decision tool were established from the following categories: burning regime, damage characteristics, fuel characteristics, ventilation characteristics, suppression characteristics, and alternative causal factors. Essentially, the span of influence from the potential damage causing attributes within a compartment were evaluated and provided weighting in the analysis of each fire pattern.

Prior probabilities were developed with input from both the predictive aspect of fire pattern causes (i.e. fire dynamics) and the evidence that remains after the fire (i.e. damage). The predictive aspect relates to the use of a few currently accepted engineering calculations and studies regarding compartment fire dynamics to establish thresholds and relationships, including flashover correlations and distances for radiant heat damage to occur. The cues identified in chapter 2 from the database of fire pattern studies were used as the evidence that remains after the fire (e.g. PG=lines of demarcation in a conical shape). The probabilities are conditional first on whether the compartment was fuel-controlled or ventilation-controlled. After this decision is made, then each fire pattern is processed through a series of BNs that illustrate the probability that the fire pattern is VG, PG, or ULG. The greatest probability identified in the results of this analysis is then recorded as the fire pattern generation for this fire pattern. In the event that the probabilities for generation are similar, then the pattern is classified as UKG.

More details on the development of the BNs please see Appendix E. For more details on a worked example, please see Appendix C. For BNs results for fire position 1, please see Appendix F.

3.5 Step 5 – Development of the Hypothetical Area(s) of Origin

The fire patterns that are classified as being generated from step 4 as plume generated (PG) and those that were undetermined in generation (UKG) will be considered as hypothetical area(s) of origin.

Table 3-4: Step 5 Questions

Question 7: Is the fire pattern plume generated or undetermined in generation?
IF yes, then this fire pattern is considered as a hypothetical area of origin (Proceed to Step 6) **IF no, then this fire pattern is not the area of origin.**

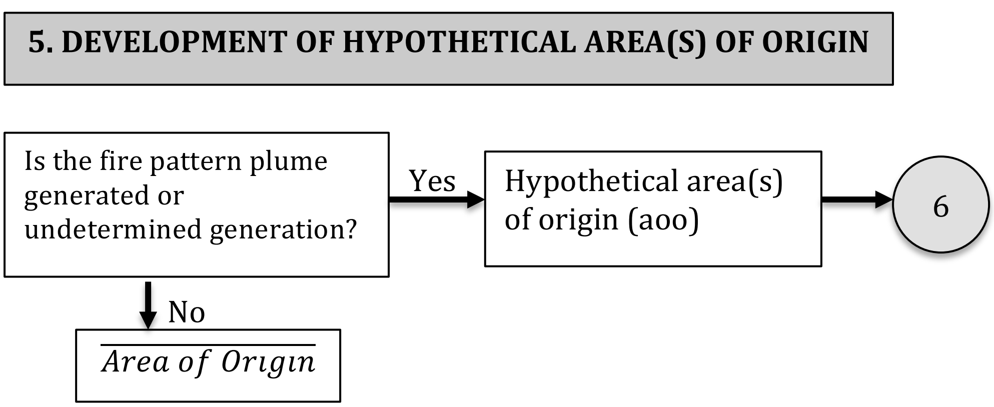

Figure 3-7: Development of Area of Origin Hypotheses

3.5.1 Area of Origin Hypothesis

The participants in this study were instructed that the PG and UKG fire patterns were to be combined and identified as a single area of origin.

3.6 Step 6 – Testing of the Hypothetical Area(s) of Origin

The hypothetical area(s) of origin are established for their likelihood as being the area of origin through a series of tests to evaluate whether a fire could have originated at this location. Each hypothetical area of origin should be tested against a decision tool, which is outside the scope of this dissertation. However, some important considerations when developing these tools will be introduced here. The decision tool would be used to differentiate those locations of damage that are consistent with being an area of origin and those that are not. Characteristics that would assist in this evaluation include logic considerations, witness statements, fire dynamics, and arc mapping. Some questions to assist with defining these characteristics include the following:

a. Logic Considerations
- Is a fuel item present within this area or evidence that fuel was present in this area?
- Is an ignition source present?

b. Witness statements
- Statements from firefighters regarding location of burning, overhaul, suppression efforts, ppv, ventilation, method/location of entry, type of extinguishment? Time of dispatch, arrival, under control, if any rekindles.
- Statements from employees, owners, occupants regarding the location of fire, smoke, flames

c. Arc Mapping
- Are there electrical arc sites?
- Is there any trend within the geographical location of arc sites?
- Does this match this hypothetical area of origin?

d. Fire Dynamics –
- Is the flame plume generated damage caused by primary or secondary burning? Can a fire starting at this hypothetical area of origin result in the fire that evolved?
- Fire spread / Fire Modeling
- Is the ignition source a competent ignition source for fuels present?
- Does damage from cluster 1 indicate flame spread to cluster η?
- Other area(s) / cluster(s) of damage that can be attributed to other causes will be considered here to assist in evaluating the development of this compartment fire.

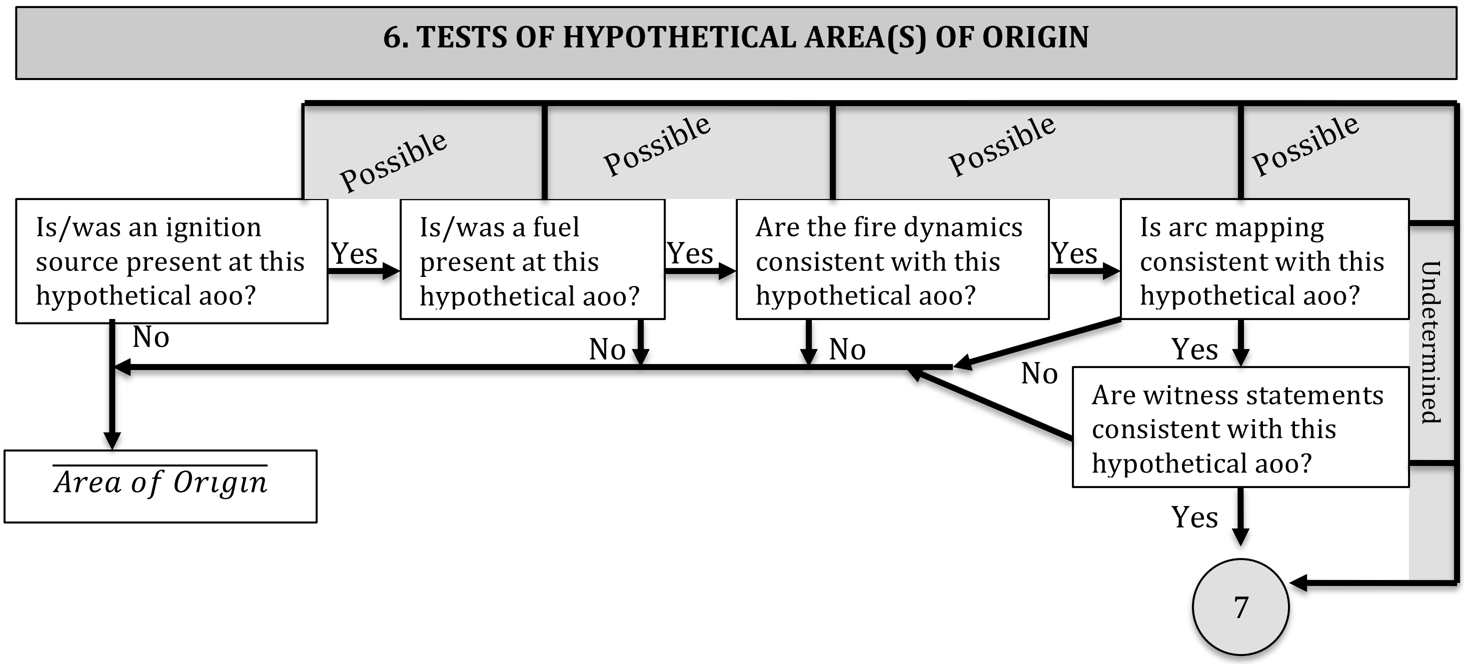

Figure 3-8: Tests of the Area(s) of Origin Hypotheses

Table 3-5: Step 6 Questions

Question 8: Does the hypothetical area(s) of origin pass the tests? Logic considerations - Is there a fuel and/or ignition source present at the hypothetical AOO? Witness statements - Do the witness statements confirm or refute the hypothetical AOO? Arc mapping - Are there electrical arc sites within or near the hypothetical AOO? Fire dynamics - Does the fire scenario from this hypothetical AOO result in the totality of the damage?
IF yes, then this area of damage is considered as part of the area of origin. If it is the only area of damage consistent with the data, then this is the area of origin. If other area(s) are consistent, then all areas should be combined and considered as the area of origin **IF no, then the cluster of damage is concluded as not the area of origin** **IF possible, then gather additioal data/analyze data more until resolution is found (i.e. feedback loop). If still no resolution or undetermined, then consider this as a 'yes'**

3.6.1 Hypothesis Testing

The participants in this study were instructed that the PG and UKG fire patterns were to be combined and identified as a single area of origin. No tests were conducted for this study.

3.7 Step 7 – Selection of the Final Area of Origin Hypothesis

The task of the fire investigator is to narrow the area of origin in order to focus the process of searching for potential ignition sources. The elimination of area(s) within a structure is an important part of this process, however, if there is damage that cannot be explained or eliminated then those areas must be included within the overall area of origin conclusion. Therefore, all the areas of damage that are identified to be consistent as a hypothetical area of origin in step 6 and any clusters of damage that cannot be explained are to be combined into a single, larger area that becomes the final area of origin determination. In relationship to the scientific method, this step corresponds to the 'select a final hypothesis' step.

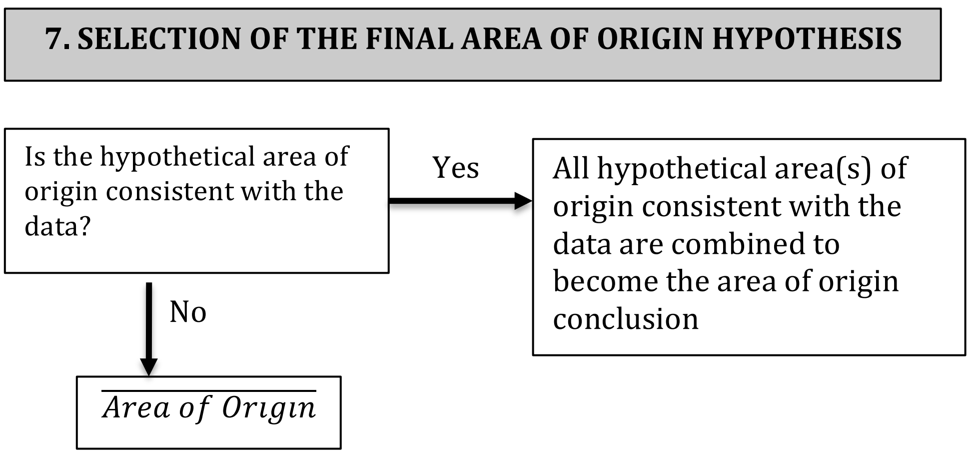

Figure 3-9: Selection of the Area of Origin

3.7.1 Area of Origin Concluded

The participants in this study were instructed that the PG and UKG fire patterns were to be combined and identified as a single area of origin.

References

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4.0 Research Methodology

The POD is a seven step process described in chapter 3 where a more detailed explanation of the POD is contained, as well please refer to previous work on this subject [2-3, 5-6].

4.1 Outline of POD

This chapter and the next are the basis for the submitted manuscript to *Fire Technology.* As such, this chapter begins by providing a basic overview of the POD so there is some overlap in information.

4.1.1 Step 1 - Value

The first step when evaluating fire damage is to determine if there is any value in analyzing the evidence further. The value question serves as a 'go' or 'no go' type of decision for further analyzing a surface or compartment. This question is equivalent to the 'defining the problem' step of the scientific method.

The value question is posed to every lining surface (e.g. walls, partitions, floors, ceilings) and content surfaces (e.g. furniture, appliances) within the compartment, as well as to the compartment as a whole. The first decision to be made in evaluating the value is to ask the simple question "is there thermal damage?". A surface exhibits thermal damage when visible or measurable physical or chemical changes occur due to the exposure to the byproducts of combustion. If the answer to the damage question is 'no' for a given surface, then that surface should not be considered near the area of origin. The phrase 'area of origin' is used many times throughout this paper despite the fact that the origin should be considered a volume within the compartment. As such, throughout this paper damage to a surface is referred to as being considered the area of origin or not, when in fact it is actually only evidence of the area of origin. If the answer to the thermal damage question is 'yes' for a given surface, then that surface is further evaluated through step 2.

4.1.2 Step 2 – Identifying Varying DOFD

The location, magnitude, and boundaries of damaged areas are identified in this step. There are several ways to perform this both visually and measurably depending upon the surface affected [3, 5]. For example, several recent studies for gypsum wallboard have provided processes to assist in the objective identification of the varying degrees of damage, including a DOFD scale for visible damage [6], a standardized depth measurement system [7-9], and the use of digital image analysis [10-12]. In relation to the scientific method, this step corresponds to the 'collect data' step.

4.1.3 Step 3 – Identifying Fire Patterns

The third step requires a comparative analysis of the data collected from step 2. The purpose of this step is to objectively identify the trends with those areas of damage within the compartment. Ultimately each surface that exhibits a cluster of damage will be ascribed as a single pattern or grouped with other damage that has been shown to extend along other surfaces as a pattern. Thus, providing the decision maker with a discrete number of patterns that must be analyzed through step four of the process. When a trend is identified along a surface, then the line(s) of demarcation that bounds this area of damage should be clearly identified, the cluster of damage identified as a fire pattern, and a number, described below, assigned to this fire pattern. In the event that the damaged surface does not have a trend or identifiable pattern, then the surface as a whole is identified as a fire pattern and a number assigned. In relation to the scientific method, this step corresponds to the 'analyze data' step.

4.1.4 Step 4 – Fire Pattern Generation

The fire patterns identified in step 3 are then evaluated and classified as to the likelihood of the causal link to the fire dynamic variables or other background factors that generated the damage [3]. Currently the *standard of care* for the fire investigation profession refers to this as fire pattern generation and provides a list of them including plume-generated (PG), upper layer-generated (ULG), ventilation-generated (VG), and suppression-generated (SG) [2-3].

Probabilistic inferences were developed between characteristics of the locations and trends of fire damage in relation to the predominant factors associated with compartment fire dynamics [5]. Bayesian theory, specifically the use of Bayesian networks (BN), has been put forward as a coherent model for interpreting forensic evidence [13]. BNs in this work were developed for determining fire pattern generation by establishing prior probabilities from both the predictive aspect of fire pattern causes (i.e. fire dynamics) and the evidence that remains after the fire (i.e. damage) [3, 14-16]. Each fire pattern identified in step 3 is processed through the relevant BN to determine the likelihood that the pattern is PG, ULG, VG, or UKG. If the fire pattern generation cannot be conclusively determined, then the fire pattern generation is noted as undetermined. In relation to the scientific method, this step corresponds to the 'analyze data' step.

4.1.5 Step 5 – Development of Hypothetical Area(s) of Origin

The fire patterns that are classified as being generated from step 4 as plume-generated or undetermined in generation are considered as hypothetical area(s) of origin. In relationship to the scientific method, this step corresponds to the 'develop hypotheses' step.

4.1.6 Step 6 – Tests of Hypothetical Area(s) of Origin

The hypothetical area(s) of origin are established for their likelihood as being the area of origin through a series of tests to evaluate whether a fire could have originated at this location. Each hypothetical area of origin should be evaluated in light of logical considerations, witness statements, fire dynamics, and arc mapping. In relationship to the scientific method, this step corresponds to the 'testing the hypotheses' step.

4.1.7 Step 7 – Selection of the Final Area of Origin Hypothesis

The task of the fire investigator is to narrow the area of origin in order to focus the process of searching for potential ignition sources. The elimination of area(s) within a structure is an important part of this process, however, if there is damage that cannot be explained or eliminated then those areas must be included within the overall area of origin conclusion. Therefore, all the areas of damage that are identified to be consistent as a hypothetical area of origin in step 6 and any clusters of damage that cannot be explained are to be combined into a single, larger area that becomes the final area of origin determination. In relationship to the scientific method, this step corresponds to the 'select a final hypothesis' step.

4.2. POD Test Methodology

This section outlines the research methodology used to test the POD for determining the area of origin. To test the reliability and validity of this prototype, a convenience sample of novices was used to apply the POD to study-provided scenarios with various areas of origin, heat release rates, and duration. A total of thirty-two scenarios were provided to the participants.

A 2x2 factorial design was utilized; the two factors were using the POD and having information about damage to contents of the room (Table 4-1). Participants were randomly assigned to each of the four treatment groups. A paired study design was not utilized in this case due to concern that examining the damage contours a second time could lead to artificially increased accuracy, resulting in accuracy rates biased in favor of the POD. The participants were provided damage contours from each scenario and asked to identify the center of their area of origin determination (also known as Point of Origin). Next, the participants were asked to select the smallest area on a diagram that encompassed the total area of origin determination for each scenario.

Table 4-1: 2x2 Factorial Design

		PROCESS FOR ORIGIN DETERMINATION (POD)	
		No POD	***With POD***
CONTENTS	***Without Contents***	Radom Assignment of 15 Participants (***No POD, w/out contents***)	Random Assignment of 15 Participants (***POD w/out contents***)
	With Contents	Random Assignment of 15 Participants (***No POD, w/ contents***)	Random Assignment of 15 Participants (***POD, w/contents***)

To conduct a study of the reliability and validity of the POD, the final area of origin determination would need to be evaluated, not the ability of the users to correctly interpret and conclude intermediate steps. Therefore, it was important that the participant was provided all of the intermediate conclusions that were needed to be drawn in order to conclude an area of origin. As such, when the participants were using the POD, they were provided with the conclusions for the first four steps. The participants were then asked to identify an area of origin in accordance with the guidelines from the POD.

The following sections of the research methodology briefly describe the preparation of information provided to the participants, development and deployment of the data collection tool, and statistical analysis procedures.

4.2.1 Preparation of Scenarios and Survey Information

A group of scenarios were developed from known variables (i.e. origin, fuels, duration). Thirty of the scenarios were based on data collected from numerical experiments, while the remaining two scenarios were based on data from physical experiments. The location and magnitude of damage for thirty-two scenarios were provided to the participants. The two physical fire tests were included for comparison purposes to reported accuracy rates of professional fire investigators.

4.2.1.1 Numerical Experiments – FDS Simulations

Numerical experiments were conducted using Fire Dynamics Simulator (FDS), v. 6.1, and its accompanying animation software Smokeview, v. 6.1, to develop an array of scenarios for fire pattern development. The numerical experiments enabled the production of predicted damage profiles based on a variety of origin scenarios with varying burning durations and heat release rates. The damage location and magnitude predictions were then provided to novices as damage contours from an unknown origin. For more details regarding the numerical experiments please see other published work [5].

Thirty FDS/SMOKEVIEW simulations of varying scenarios were completed to evaluate what variables had the greatest influence on the location and magnitude of heat flux within a prescribed compartment fire. The intent of these numerical experiments was to develop varying locations and magnitude of predicted damage for use in testing the prototype process.

The compartment evaluated was a single compartment (3.66m x 3.66m x 2.44m) with one doorway that served as the ventilation opening. The fire position (origin) was varied throughout the simulations between against the wall (fire positions 1-3, 5-6) and near wall fires (fire position 4) (Fig 4-1). The time integral heat flux for every surface within each simulation was recorded because it has been shown to be a useful and simple approximate metric for damage [7-9].

Contour plots were created from the time integral heat fluxes throughout the compartment, which illustrated the location and magnitude of heating within each simulation at various time steps. The contour plots were then utilized as the degree of fire damage for testing the POD. The numerical experiments were not intended to provide exact location and magnitude of damage, but more of a relative degree of damage throughout the compartment that would serve as a good test of the POD.

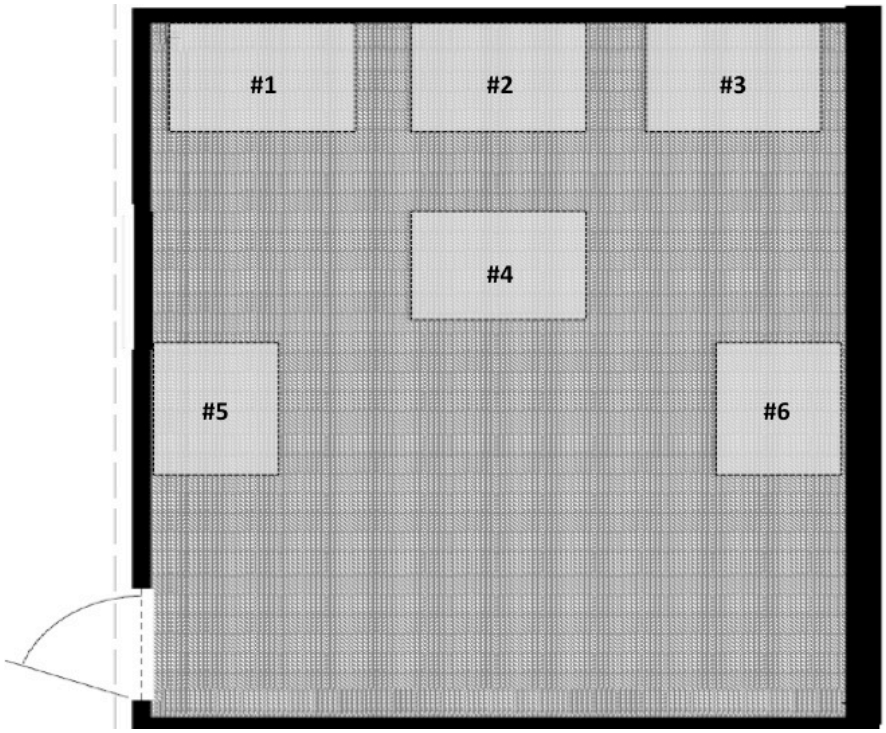


Fig 4-1: Simulation compartment layout – floor plan with fire positions identified

4.2.1.2 Selection of Scenarios

The numerical experiments provided a set of scenarios that would serve as a means to assess the POD when utilized by novices. The simulations provided contour plots for each fire position, with five peak heat release rates at 17 time step intervals (every 60s up to 1000s). A total of thirty numerical experiments were used for this study. These included five of the six fire positions at two different peak heat release rates at three different time step intervals (Table 4-2). Fire position five was not evaluated due to the lack of any discernable difference between the peak heat release rates and time step intervals, most likely due to the majority of the heat exiting the ventilation opening. Two peak heat release rates, 1.5MW and 4MW, were chosen to reflect the more challenging conditions to test the POD. Three time step intervals for each peak heat release rate were chosen to best represent varying conditions within the compartment, which include 120s, 360s, and 900s. The 120s time step interval will clearly reflect fuel-controlled conditions, while the 360s and 900s time step intervals will represent a short and long duration ventilation-controlled condition.

The location and magnitude of damage for two additional physical experiments was included with the array of numerical scenarios provided to the participants. These two specific physical fire tests were included due to reported accuracy rates of professional fire investigators [17-19]. The first physical experiment provided was one conducted in 2008, in which a 5.7% accuracy rate was identified in area of origin determination based on professional fire investigators determining the quadrant of the room [17-18]. This study will be referenced as the ATF study throughout this work. The second physical experiment included was performed in 2012, in which a 74% accuracy rate was identified in area origin determination. This study will be referenced as the FIODS study throughout this paper [19].

Table 4-2: Scenarios provided to each participant

NUMERICAL EXPERIMENTS							
	Fire Position						
Peak HRR	**1**	**2**	**3**	**4**	**5**	**6**	
1500 kW	120s	120s	120s	120s	N/A	120s	Time steps
	360s	360s	360s	360s	N/A	360s	
	900s	900s	900s	900s	N/A	900s	
4000 kW	120s	120s	120s	120s	N/A	120s	
	360s	360s	360s	360s	N/A	360s	
	900s	900s	900s	900s	N/A	900s	
PHYSICAL EXPERIMENTS							
ATF Study	Carman & Oulette (2008)			Reported accuracy 5.7%			
FIODS Study	Tinsley & Gorbett (2012)			Reported accuracy 74%			

4.2.1.3 Development and Presentation of Degree of Fire Damage Data

Varying degrees and location of damage were provided to the participants. To enable this, contour plots of damage were developed from the numerical and physical experiments.

The numerical experiments collected the total imposed heat flux for the duration of the simulation. This time integral gauge heat flux boundary file was evaluated using Smokeview. The grid of devices for each wall and ceiling surfaces were evaluated as contour plots. A normalized damage scale was provided based on the total heat fluxes identified within the compartment. This scale was normalized to the greatest total heat flux identified from all of the simulations (Fig 4-3). Participants in each of the four treatment groups used these contour plots of damage.

A degree of fire damage assessment was conducted on the physical experiments to develop contour plots of damage. The ATF study was prepared using the DOFD method [6]. The FIODS study was prepared based on measurements of the depth of calcination. The contour plots of damage were then prepared using the same MATLAB code as the numerical experiments. A similar damage scale as identified for the simulations was also used (Fig 4-3).

4.3 Development and Deployment of Data Collection Tool

To test the reliability and validity of the POD, participants (novices) were asked to complete an origin determination exercise using the data from thirty of the numerical experiments and two physical experiments. Participants were randomly assigned to each of the four treatment groups. A total of thirty-two scenarios were provided to the study participants.

4.3.1 Data Collection Procedures

A convenience sample of novices was used to assess the reliability and validity of the POD. The participants included 60 undergraduate fire protection engineering technology students with no formal training or practical experience in fire investigations. Although this was not a random sample, the participants were reasonably representative of typical novices. Participants were randomly assigned into the four treatment groups (POD with contents, POD without contents, no POD with contents, no POD without contents; 15 novices per group) and provided damage contours from each scenario. The participants were asked to first identify the center of their area of origin determination and then select the smallest area on a diagram that encompassed the total area of origin determination for each scenario.

Responses from participants were collected electronically using Qualtrics survey software [20]. This platform provided the participants with a simple method to record the center of their area of origin determination and the regions that encompassed their total area of origin determination. The participants were not able to return to a scenario once submitted. The participants were not permitted to talk to each other as they performed the study.

The participants accessed the data collection tool through a website link provided via email. The tool was designed to randomize the scenarios for each participant. This randomization of the scenarios was done to reduce the effects of sequencing from simple to more complex cases, as well as reduce any effects due to fatigue.

Participants were not aware that the data they were evaluating was from numerical simulations or physical fire tests, only that the data they were reviewing was contour plots of damage. A color-coded generic damage scale was provided with the plots representing white as less damage and black as more damage (Fig 4-3).

Participants in all four treatment groups were provided similar damage contour plots for the walls and ceiling; however, the damage contour plots of the contents were provided only to participants in the treatment groups with information about contents. Including availability of information about contents as a factor allows for the evaluation of a relationship between having content information and not having content information.

Instructions were provided to each participant. **T**he instructions for participants in the treatment groups not utilizing the POD were simply that there are a total of 32-sets of images that you will be shown, please select the center of your area of origin and then select the smallest area that encompasses your area of origin determination.

The instructions for participants in the treatment groups utilizing the POD were similar, except a sentence was added to indicate that the participants were to follow the specific instructions throughout.

For all treatment groups, these instructions were followed by an image of an exploded view diagram to prepare participants for the orientation of the provided images (Fig 4-2). A description of an exploded view diagram was also provided with the image in order to better explain the exploded view diagram.

After reading these initial instructions and viewing the orientation of the exploded view diagram, the participants would then simply click on a forward button at the bottom of the screen and begin to evaluate each of the 32 scenarios. Sixteen of the scenarios were randomly presented to the participants. After half of the scenarios were completed, an attention-verification question was asked to ensure that participants were actively reviewing instructions and making conscious decisions rather than simply haphazardly identifying the origin center and origin regions. The attention verification question used in this study was selected as one that has been shown to ensure valid responses for online surveys [21]. Following the attention-verification question, the final sixteen scenarios were randomly presented to the participants.

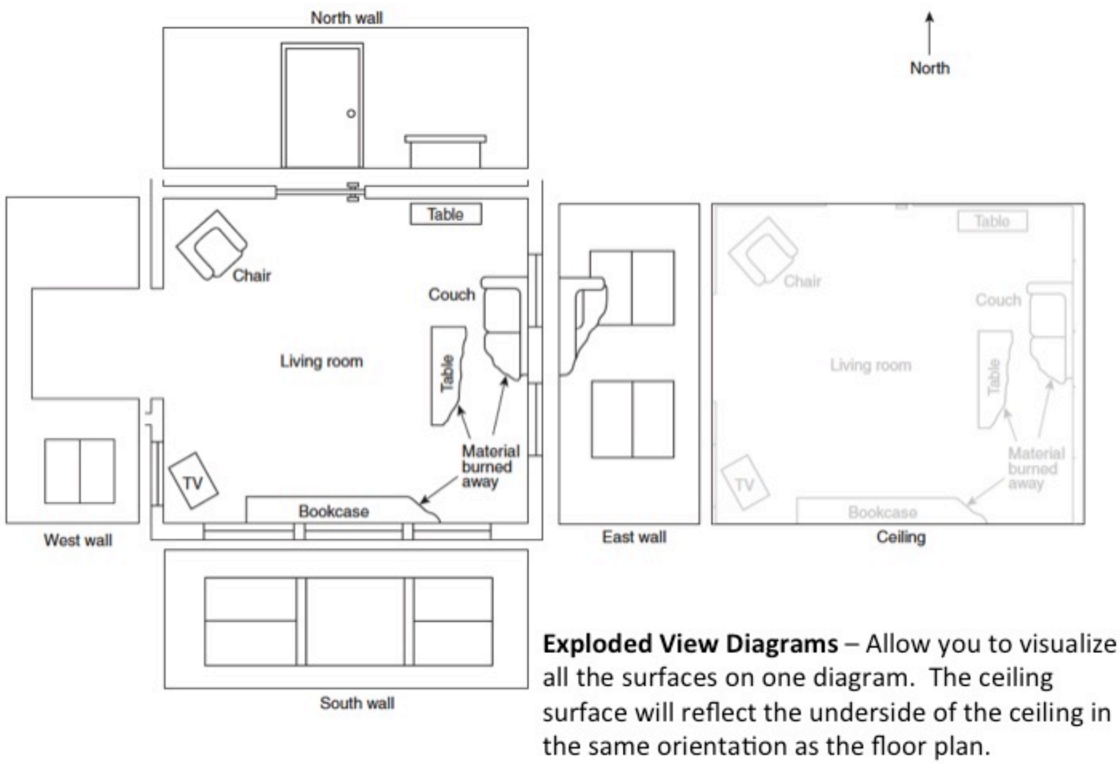


Fig 4-2: Exploded view diagram image and instructions provided to participants

4.3.2 Identifying Origin without the use of the POD

Two of the treatment groups were to assess the accuracy and variability of the participant responses without any process provided. This section briefly outlines the sequencing of questions provided to the participants. The complete data collection tool has been provided in previously published work [5]. One of the treatment groups was provided contour plots reflecting location and magnitude of damage to the walls and ceiling (no POD without contents) (Fig 4-3). The other treatment group was provided the same contour plots of the walls and ceiling with the addition of contour plots of damage to the contents of the room (no POD with contents) (Fig 4-4).

Participants were provided an exploded view diagram of a single compartment for each scenario (Fig 4-3). All participants were provided the following wall and ceiling contour plots of damage with a description that contour lines and changes in color are used to illustrate the varying degrees of damage on each ceiling and wall surfaces, and that the rectangular shapes in the diagram are combustible contents.

The participants were asked to then make two conclusions related to their area of origin determination. First, they were asked to select the center of the area of origin by clicking the mouse in that location (Fig 4-5). The software recorded the X- and Y-position of the click. Secondly, the participants were asked to select all the regions that encompass the smallest area of origin. The regions were rectangular grid spaces approximately the size of the combustible items within the compartment (Fig 4-6). The participant could select multiple regions. The software would record the region as 'on' or 'off' depending on whether the region was selected by the participant.

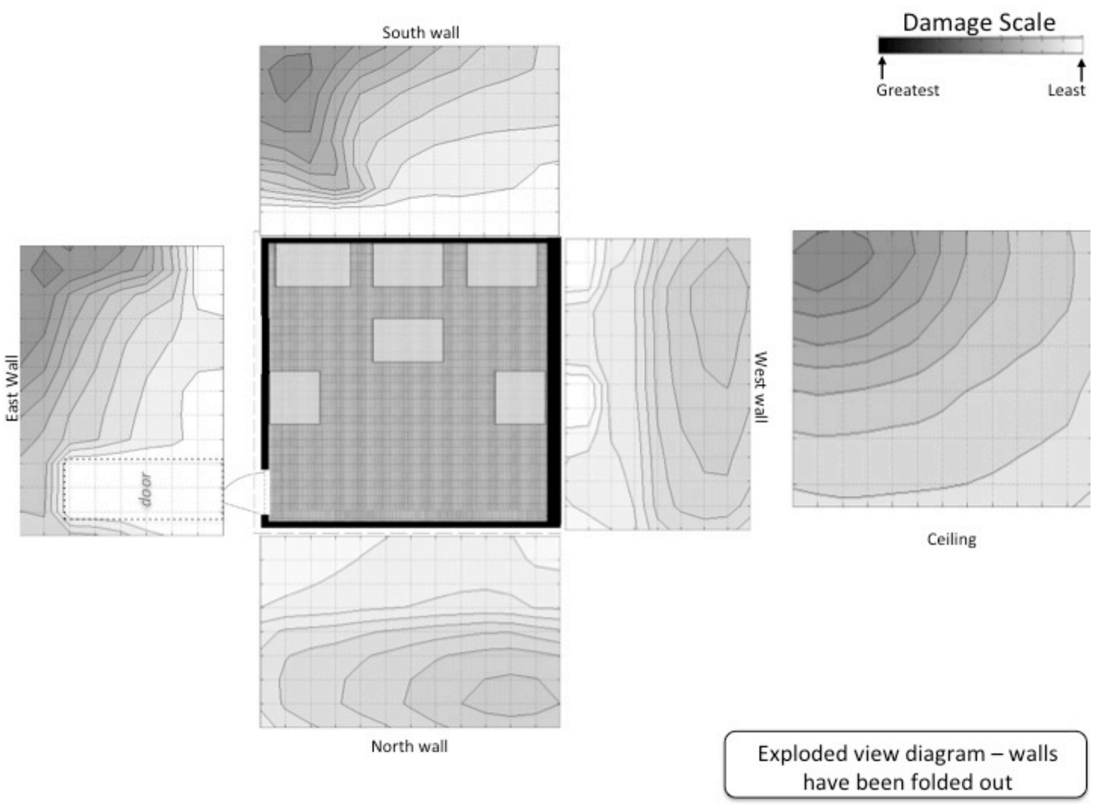


Fig 4-3: Exploded view diagram with contour plots of damage to walls and ceiling with damage scale

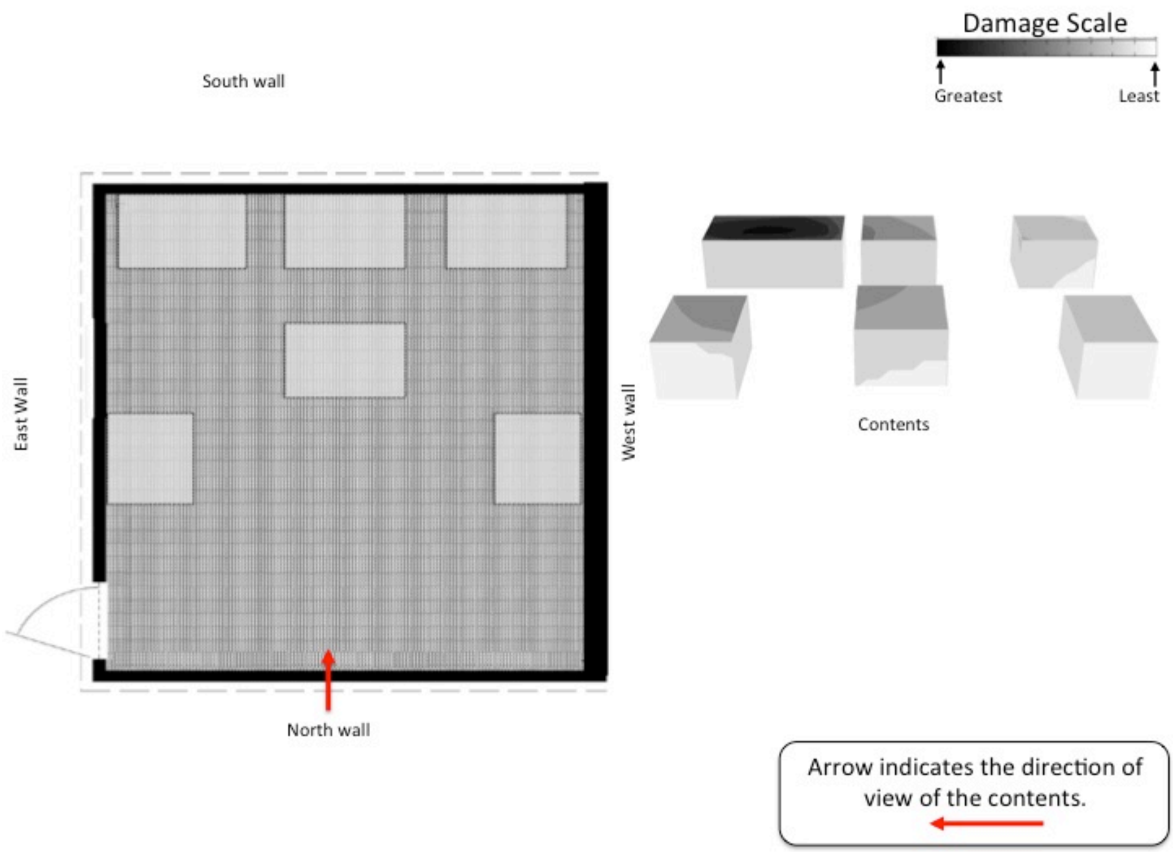


Fig 4-4: Contour Plots of Damage to Contents

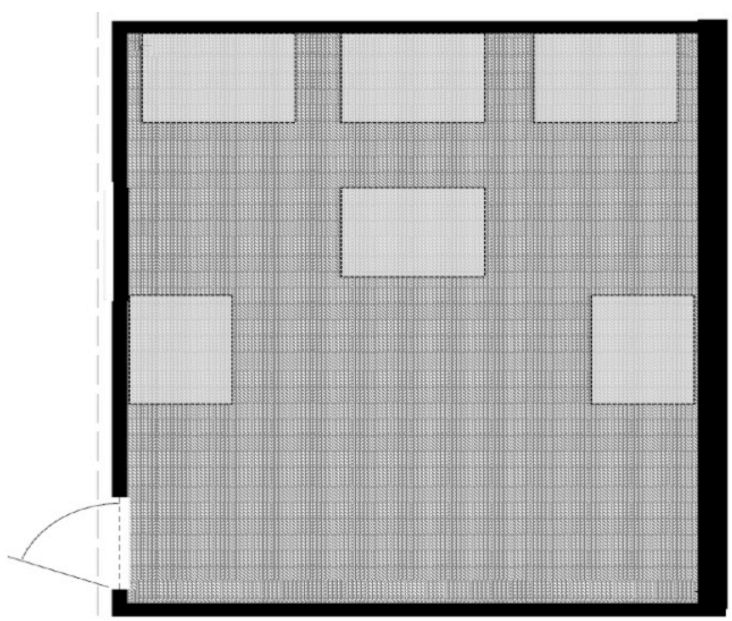


Fig 4-5: Diagram for center of area of origin determination

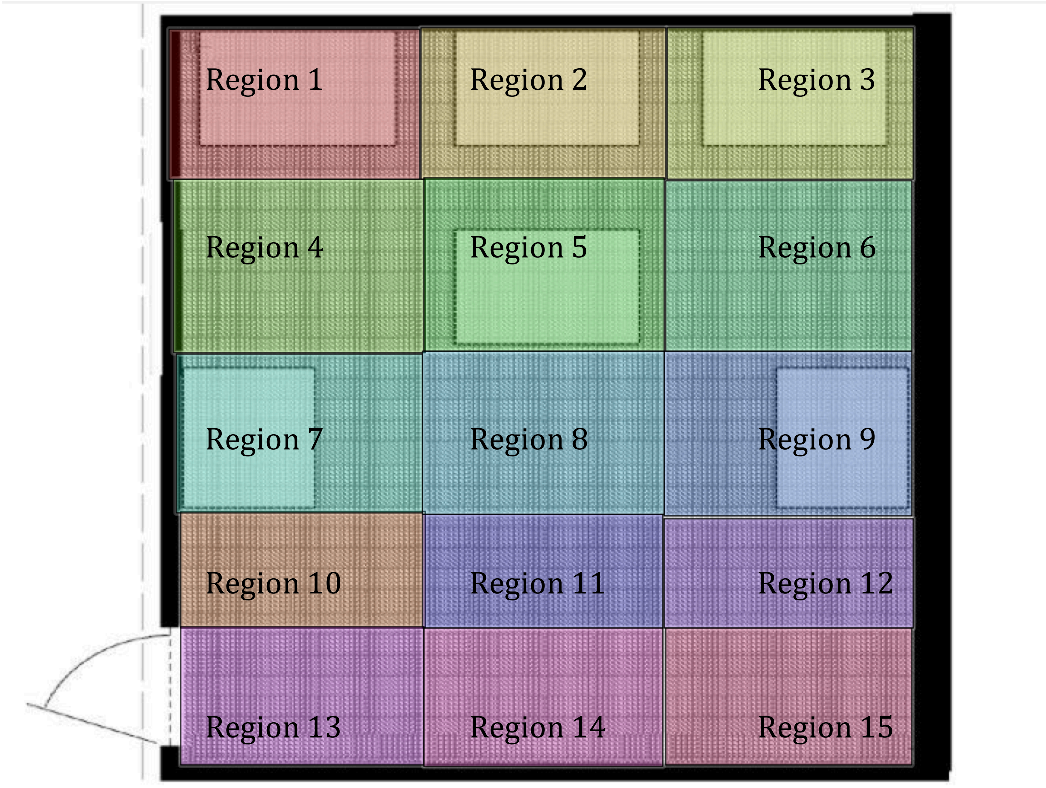


Fig 4-6: Regions to be selected for area of origin determination

4.3.3 Identifying Origin using the POD

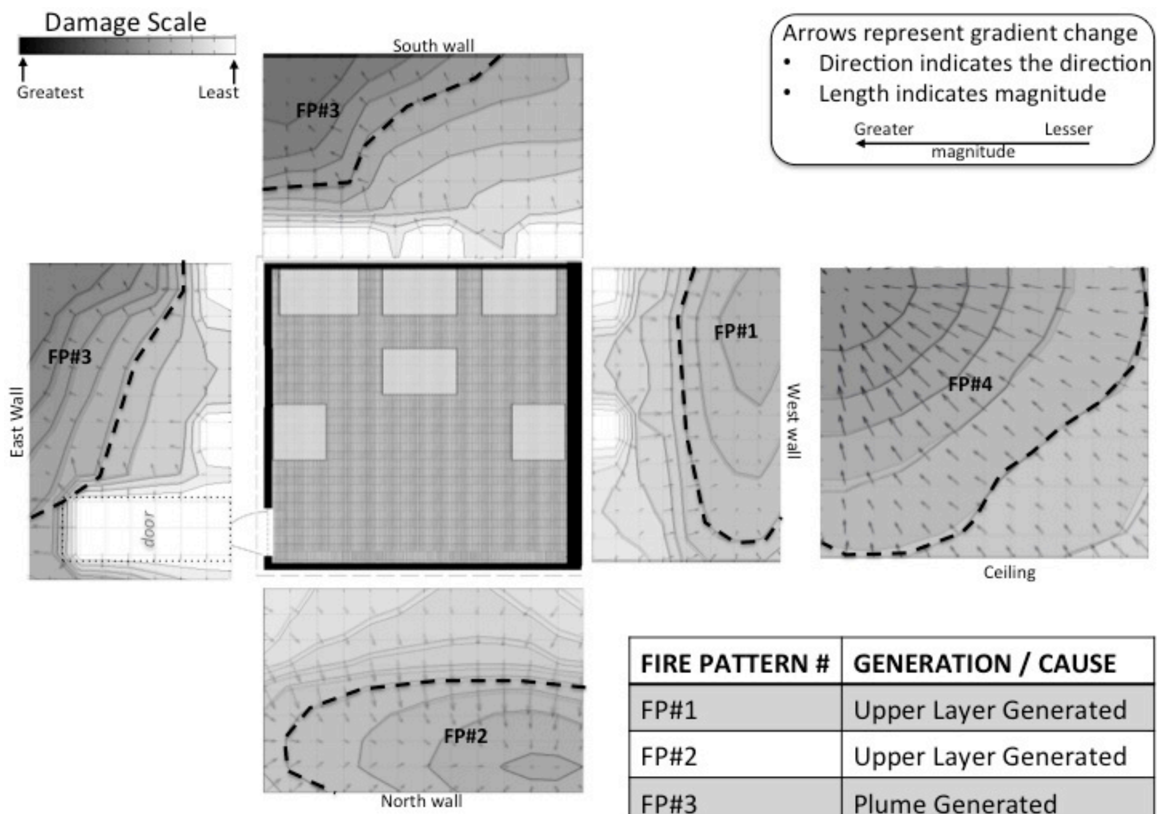
Participants in the treatment groups utilizing the POD were used to assess the accuracy and variability with a provided process (POD). This section briefly describes the sequencing and layout of the questions provided to the participants using the POD. One of the treatment groups was provided contour plots reflecting location and magnitude of damage to the walls and ceiling, numbered and labeled fire patterns, a table identifying the generation for each fire pattern, and contour plots of damage to the contents (POD with contents). The other treatment group was provided the same contour plots of the walls and ceiling, labeled and numbered fire patterns, and table listing the fire pattern generation, however, this group was not provided contour plots of damage to the contents of the room (POD without contents).

Each participant was instructed to follow the provided guidelines in order to determine the area of origin. Again participants were provided with exploded view diagrams with contour plots depicting damage to the walls and ceiling; however, the participants utilizing the POD were provided with dashed lines outlining areas along the contour plots that were labeled and sequentially numbered as fire patterns. A table was also provided within this diagram that identified the most likely generation or cause for the fire pattern (Fig 4-7). The options for fire pattern generation included upper layer generated, ventilation generated, plume generated, or undetermined. The instructions provided to the participant for this step were as follows:

> **FIRE PATTERNS NUMBERED & THEIR IDENTIFIED CAUSE**
> Below are exploded view diagrams of a single compartment. The boundary of each fire pattern has been noted on the diagram by a dashed-line. Each fire pattern identified within this scenario has already been identified and provided a number (FP#1=Fire Pattern #1). In the bottom-right corner of the image each fire pattern is assigned a cause for that pattern (fire pattern generation). The options for generation include upper layer generated, plume generated, ventilation generated, or undetermined. Particular attention should be given to those patterns identified as PLUME or UNDETERMINED generation, as these will assist in determining the area of origin. The rectangular shapes in the diagram are combustible contents.

Each participant was then instructed to identify the center of their area of origin determination by clicking on a diagram (Fig 4-5). However, the instructions for participants in the treatment groups using the POD explicitly instructed that only identified plume generated and undetermined fire patterns were to be considered as the area of origin.

The participants were then instructed to identify all the regions that encompass the smallest area of origin (Fig 4-6); however, participants were instructed that the fire patterns that were classified as undetermined and plume generated would be considered as the area of origin and that the participant would have to select all the regions that included these fire patterns.



FIRE PATTERN #	GENERATION / CAUSE
FP#1	Upper Layer Generated
FP#2	Upper Layer Generated
FP#3	Plume Generated
FP#4	Plume Generated

Fig 4-7: Contour Plots with Identified Fire Patterns and Fire Pattern Generation

4.4 Statistical Analysis

The two measures used to assess the POD were validity and reliability. For the purposes of this dissertation, reliability is defined as "the same results are obtained in each instance the test procedure is being performed – its consistency" and validity is defined as "the ability of a test procedure to measure what it is supposed to measure – its accuracy" [22].

4.4.1 Reliability Measures

Reliability was evaluated by examining the consistency of participants arriving at the same determination for location of the true origin. The distances between the X- and Y-coordinate selected by the participants as location of origin and the true origin was calculated for each of the 32 scenarios. While this measure does not incorporate directionality, we can conclude that the POD group is more consistent in their selection of origin if the variability of the distances is smaller for the participants utilizing the POD compared to those using no process. Further, the POD was a more reliable method of determining the origin.

4.4.2 Validity Measures

Validity was evaluated by assessing accuracy of origin among the participants. Accuracy was defined as both true accuracy and accuracy according to the POD. Accuracy was measured using the X- and Y-coordinates of the center of origin and using the origin regions. In some of the scenarios, use of the POD could lead to the origin being defined as the whole room; in that case, the center of the room would be the center of origin and all regions would be selected as origin regions. It is of note that in some cases, true region accuracy is easier to achieve than method region accuracy. For true region accuracy, a participant would only need to select the correct origin region (e.g., Region 1), while for method accuracy they would need to select all of the correct origin regions (e.g., all regions if the POD led to origin center at the center of the room).

The true origin was considered as the combustible item. Therefore, the center point for each combustible item was selected as the true origin center. In the case that the method led to the origin at the center of the room, the coordinates for the center of the room were selected as the method origin center. For each scenario, the participant's identified center of origin was considered accurate if it was contained in a circle with radius 45 pixels (diameter of 90) around the true origin center. A bivariate analysis was performed to compare accuracy between those utilizing the POD and those using no process. The Chi-Square Test of Independence was not appropriate in this study as the small sample size could lead to contingency table expected cell counts of less than five. Fisher's Exact Test of Independence is more accurate than the Chi-Square Test when expected values are small and it is the appropriate bivariate analysis method when both variables are nominal (accurate vs. not accurate, POD vs. no process). Fisher's Exact Test will be used for comparison of accuracy between groups with a significance level of $\alpha=0.05$ throughout. A higher proportion of participants utilizing the POD accurately identifying origin center compared to those using no process indicates the validity of the POD.

The true region of origin contains the combustible item. For each scenario, a participant's region of origin was considered accurate if they selected the region containing the combustible item. Both true region accuracy and method region accuracy were compared between those utilizing the POD and those using no process with Fisher's Exact Test. Similar to center of origin, a higher proportion of participants utilizing the POD accurately identifying origin region compared to those using no process indicates the validity of the POD.

4.5 Limitations

Due to the large frequency of images the participants were asked to assess, participant fatigue was a potential limitation. However, the time to completion was estimated to be no more than thirty minutes and the order in which scenarios were presented was randomized.

In practice, the information required for each step would have to be collected by the investigator. While a significant component of the POD, most of that information was provided to participants utilizing the process in this study. If accuracy rates are higher for those participants compared to participants using no method, this is most likely a result of following the steps outlined in the process rather than differences in ability to collect the information required for each step. This aspect of the study design allowed for a direct evaluation of the POD.

This process did not evaluate the third dimension to the origin determination; elevation of fire base was not asked of the participants. Additionally, participants were not permitted to select multiple origins.

5.0 Results and Discussion

This chapter has been organized into reliability results and validation results. The results for each measure will be described below with a focus on the change related to the use of the POD.

5.1 Reliability Results

The reliability measure examined the consistency of participants arriving at the same determination for location of the true origin. The distances between the X- and Y-coordinate selected by the participants as location of origin and the true coordinate for origin was calculated for each of the 32 scenarios. While this measure does not incorporate directionality, we can conclude that the POD group is more consistent in their selection of origin if the variability of the distances is smaller for the participants utilizing the POD compared to those using no POD.

The variance (σ^2) provides a good measure for comparing the reliability of the POD in comparison to those that did not use the POD. The variance of the given answers by the participants without the POD was compared to the variance with the participants using the POD. The variability in distances was compared from the participants' selected center of origin and the true center of origin to determine if those using the POD are answering "closer together." A decrease in variability was seen at the individual scenarios level in 21 of the 32 scenarios (66%), the variability in those distances was smaller for those using the POD than those not using the POD (Table 5-1). There were 19 of 30 simulation scenarios (63%) that demonstrated less variability when using the POD and both physical experiments had a decrease in variability when the POD was used (Fig 5-1) [5].

Table 5-1: Reliability Measures – Overall Variability Change and Test for Equality of Variances

OVERALL VARIABILITY CHANGE			
	Number of Scenarios	**Total scenarios**	**%**
Decreasing variability w/POD	21	32	66
Increasing variability w/POD	11	32	34
TEST FOR EQUALITY OF VARIANCES			
	Without POD	**With POD**	
Mean (μ) distance from true origin	105.46	86.93	
Standard Deviation (σ)	10.81	10.58	
Median distance from true origin	105.79	88.98	

Another method to evaluate the reliability of the POD was accomplished through plotting each answer set as a scatter plot, finding the centroid of that answer set, calculating the distance from that centroid to all answers, and then calculating the 95% confidence interval of the answer set. The centroid, or the geometric center of the data, was calculated for the answer sets for each scenario without the POD and with the POD. The distance between each X- and Y-coordinate selected by a participant as the center point of his or her area of origin was then calculated from this centroid coordinate. From this, a 95% confidence interval distance was calculated and used as the diameter of an ellipse that centered on the centroid for the answer set. If the diameter of the ellipse is smaller when using the POD, then it can be concluded that the answers were more consistent and therefore more reliable with the use of the POD [5].

An example of this comparison has been provided for fire position 1 at 4MW, 900s (Fig 5-1). The coordinate for the true origin point was also plotted. The closer the centroid was to the true origin coordinates, the more accurate the answer set was, which indicates validity of the POD. The figures illustrate two data sets (1) without POD and (2) with POD, two ellipses each with a diameter based on the 95% confidence interval for the distances for each data set, centroid for both data sets, and the true center point. Evaluating the diameter of the ellipses can assess reliability. The dashed line ellipse illustrates the 95% confidence interval distance diameter for the answer set without the POD, while the solid line ellipse illustrates the 95% confidence interval distance diameter for the answer set with the POD. The blue dots represent the answers from participants without the POD, green asterisks represent the answers from participants with the POD, the blue square indicates the centroid of the data set without POD, the black square indicates the centroid of the data set with the POD, and the red square indicates the true origin point (Fig 5-2).

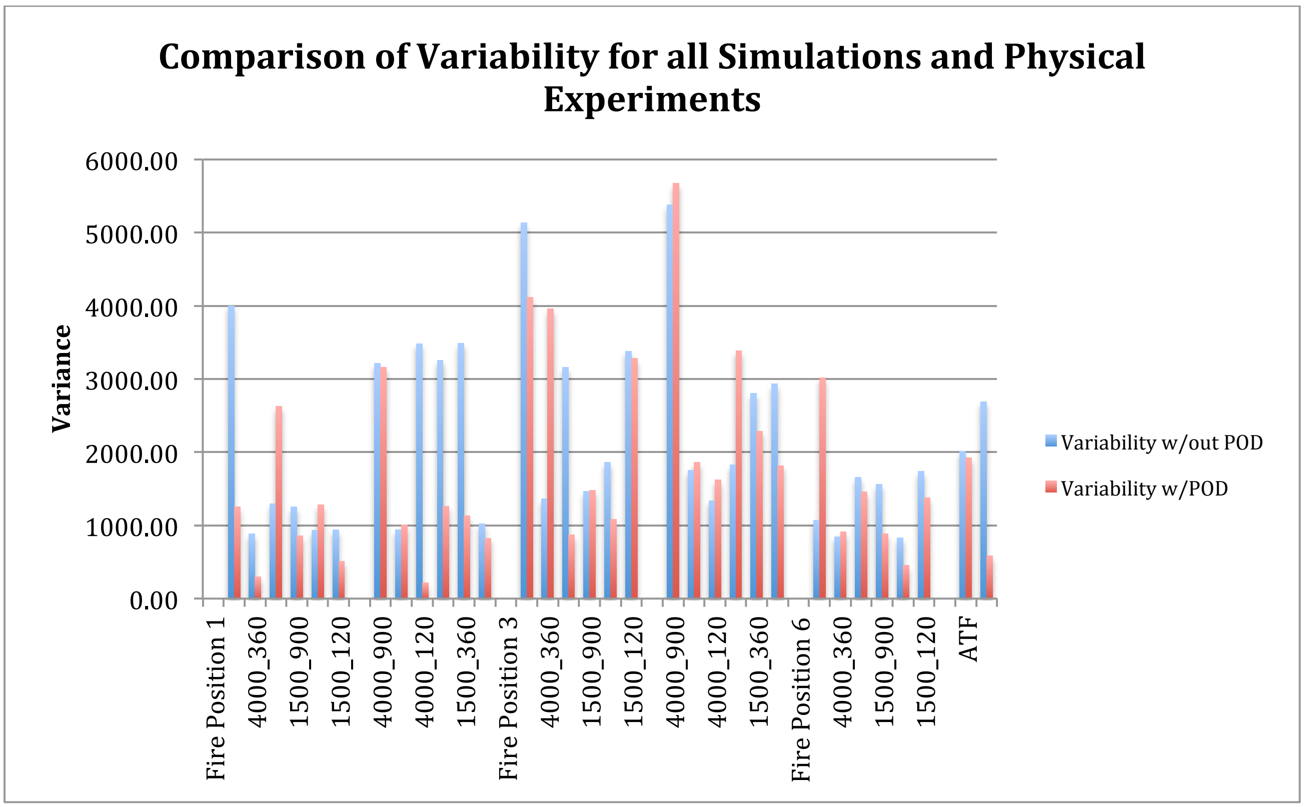


Fig 5-1: Variability for all 32 scenarios with and without the POD

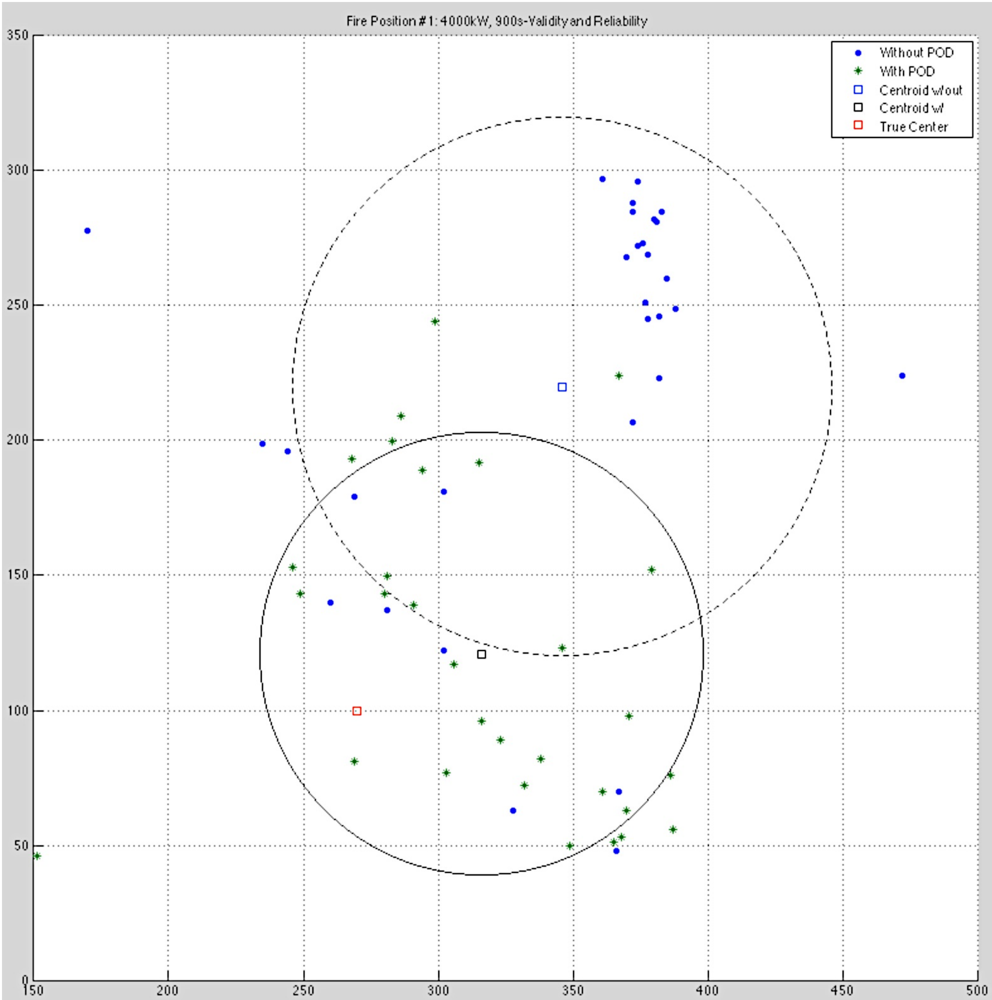


Fig 5-2: Scatterplot of answer sets with centroids identified (solid line is ellipse for answer set using POD, dashed line is ellipse for answer set without POD) – Fire Position #1 4000kW, 900s

As confirmation to the variance results from above, 21 of 32 (66%) scenarios had a smaller diameter ellipse for the answers using the POD. A total of 24 of the 32 (75%) scenarios had their centroid closer to the true center when using the POD, which is discussed in greater detail in section 4.2.3 of this paper. Of those 11 scenarios where the POD results were not as consistent (i.e. larger diameter and larger variance), the centroid was closer to the true center with using the POD.

The greatest variability was consistently observed with the higher heat release rate simulations at the longer durations. This was expected based on previous review of the literature. Interestingly, four of the eleven that demonstrated greater variability was found with fire position 4 (near wall fire).

5.2 Validity Results

The validation studies were purposefully setup to evaluate the question for validity at varying levels. The first level was to evaluate whether the participants accurately identified the region that was the true area of origin. Next, the validation question evaluated whether or not the participants chose the correct region(s) reflected by the POD (method). Finally, the validation question evaluated whether the center point identified by the participants were within the established area of origin and the influence of the POD on distance away from the origin.

5.2.1 Region Accuracy

The first validation test evaluated which region(s) the participants selected as their area of origin (Fig 4-6). The participant was classified as accurate if they selected the region that reflected the region identified as the true origin. A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 19 out of 32 scenarios (59%), a decrease in accuracy when using the POD in only 6 out of 32 (19%), and no change in accuracy when using the POD in 7 out of 32 scenarios (22%) (Table 5-2). None of the six scenarios that decreased in accuracy when using the POD were shown to be statistically significant. It was found that 6 out of the 19 scenarios (32%) that were shown to increase in accuracy when using the POD were statistically significant (Table 5-2). The nonparametric Wilcoxon test is a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed. Overall there is a statistically significant increase in accuracy rates for the true origin region when the POD was used (z=3.48, p=0.001) (Table 5-2).

Table 5-2: Validation Results – Comparison of Region Accuracy

Overall Comparison of Region Accuracy Rates without and with the POD			
	Number of scenarios	**Total scenarios**	**%**
Increasing accuracy with the method	19	32	59
No change in accuracy	7	32	22
Decreasing accuracy with method	6	32	19
Statistical Significance Evaluation			
	# showing significant increase	**Total increasing scenarios**	**%**
Statistically significant increase (alpha =.05)	6	19	32
Test for Overall Significance			
	Without POD	**With POD**	
Mean (μ) accuracy rate	0.83	0.92	
Standard Deviation (σ)	0.12	0.14	
Median accuracy rates	0.78	0.97	
Independent samples t-test to compare means	t=2.74	p=.01	
Wilcoxon two-sample test to compare medians	z=3.48	p=0.001	

The general trend with the simulation data was a decrease in accuracy with the higher heat release rates and longer duration simulations (Fig 5-3). Fire position 4 (near wall fire) had the lowest accuracy rates of any of the simulations, however, the most significant increases in accuracy were demonstrated when the POD was used at this fire position. Both of the physical experiments had a statistically significant increase ($p<0.05$) in accuracy when using the POD (Fig 5-3).

A potential limitation with these results comes from the imposed definition of accuracy. A participant was classified as accurate when the region identified as the true region was selected, regardless of the number of regions selected by the participant. This potentially allows for an artificially high accuracy rate should the participant select all of the regions for all scenarios. Each scenario was evaluated to identify what percentage of participants selected each region with and without the POD to examine this possibility. It was found that the majority of the scenarios had greater percentage of participants selecting the true region of origin, followed by a slight decrease in percentages of participants selecting 1-2 adjacent regions around the true origin, and then a consistent decrease in percentages and number of regions selected moving away from the true origin. Many of the scenarios had several regions not selected by any of the participants, which is evidence that an artificially high accuracy rate was not influenced by random selection of all regions.

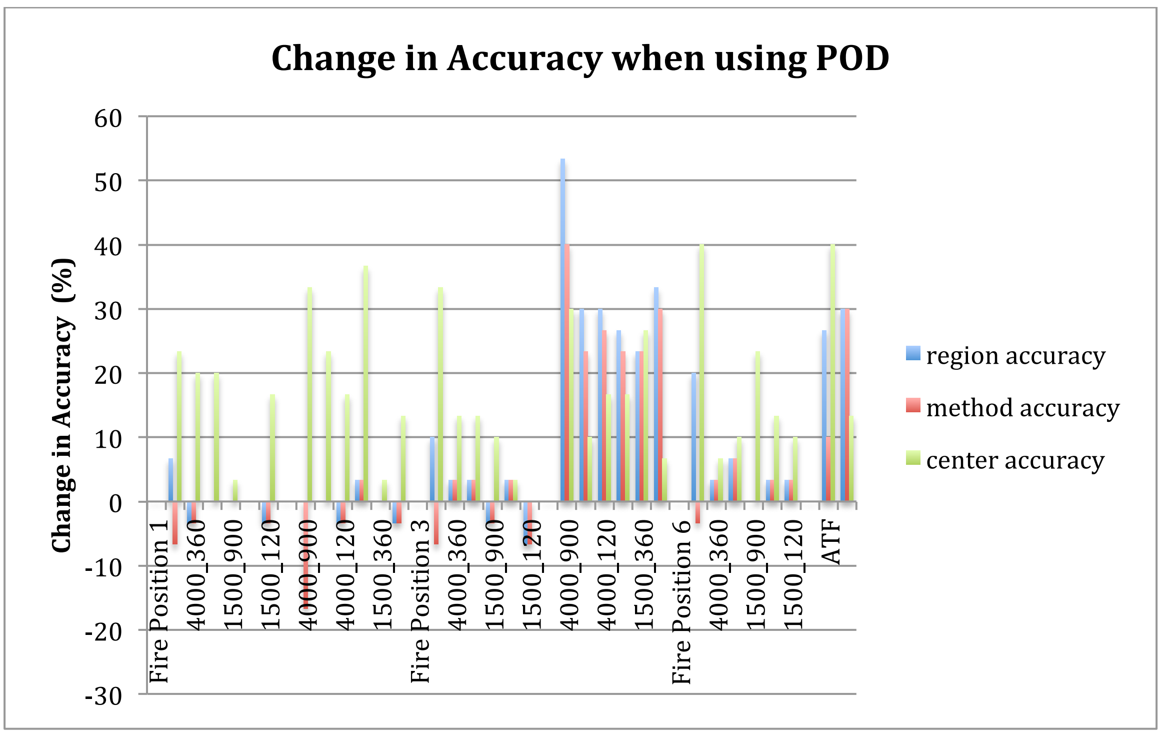


Fig 5-3: Change in Accuracy for all 32 scenarios when using the POD for all Validation Measures

5.2.2 Selection of Regions in Accordance with the POD-Method Accuracy

The next validation test evaluated which region(s) the participants selected as their area of origin in comparison to what regions should have been selected as identified by accurate use of the POD. This evaluation is referred to as method accuracy. The participant's selection was classified as accurate if they selected the exact region(s) that reflected the region(s) identified as the area of origin from the POD. A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 16 out of 32 scenarios (50%), a decrease in accuracy when using the POD in 10 out of 32 (31%), and no change in accuracy when using the POD in 6 out of 32 scenarios (19%) (Table 5-3). None of the ten scenarios that decreased in accuracy when using the POD were shown to be statistically significant. It was found that 3 out of the 16 scenarios (19%) that were shown to increase in accuracy when using the POD were statistically significant (Table 5-3). Again, the nonparametric Wilcoxon test was found to be a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed. Overall there is a statistically significant increase in accuracy rates for identifying the method regions when the POD was used ($z=2.11$, $p=0.04$) (Table 5-3).

Table 5-3: Validation Results – Comparison of Method Accuracy

OVERALL COMPARISON OF METHOD ACCURACY RATES WITHOUT AND WITH THE POD			
	Number of scenarios	**Total scenarios**	**%**
Increasing accuracy with the method	16	32	50
No change in accuracy	6	32	19
Decreasing accuracy with method	10	32	31
STATISTICAL SIGNIFICANCE EVALUATION			
	# showing significant increase	**Total increasing scenarios**	**%**
Statistically significant increase (alpha=.05)	3	16	19
TEST FOR OVERALL SIGNIFICANCE			
	Without POD	**With POD**	
Mean (μ) accuracy rate	0.83	0.89	
Standard Deviation (σ)	0.12	0.14	
Median accuracy rates	0.78	0.94	
Independent samples t-test to compare means	t=1.71	p=.1	
Wilcoxon two-sample test to compare medians	z=2.11	p=0.04	

The general trend with this analysis was that the accuracy decreased for those simulations that had higher heat release rates and longer durations. Fire position 4 had the lowest accuracy rates, however, it had the most significant increases in accuracy when the POD was used. Both of the physical experiments increased in accuracy with the use of the POD. The FIODS study had a statistically significant increase ($p<0.05$) in accuracy when using the POD (Fig 5-3).

5.2.3 Center Point Accuracy

There are two ways to evaluate accuracy using the X- and Y-coordinates of the center of the origin. The first method to evaluate accuracy using the X- and Y-coordinates is to evaluate whether or not the participant coordinates fell within the prescribed area of origin. For each scenario, the participant's identified center of origin was considered accurate if it was contained in a circle with radius 45 pixels (diameter of 90) around the true origin center (Fig 5-3). A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 30 out of 32 scenarios (94%), a decrease in accuracy when using the POD in 0 out of 32 (0%), and no change in accuracy when using the POD in 2 out of 32 scenarios (6%) (Table 5-4). It was found that 7 out of the 30 scenarios (23%) that were shown to increase in accuracy when using the POD were statistically significant (Table 5-4). The nonparametric Wilcoxon test was again a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed. Overall there is a statistically significant increase in accuracy rates for the center point when the POD was used ($z=4.74$, $p<0.0001$) (Table 5-4).

Table 5-4: Validation Results – Comparison of Center Point Accuracy

OVERALL COMPARISON OF CENTER POINT ACCURACY RATES WITHOUT AND WITH POD			
	Number of scenarios	**Total scenarios**	**%**
Increasing accuracy with the method	30	32	94
No change in accuracy	2	32	6
Decreasing accuracy with method	0	32	0
STATISTICAL SIGNIFICANCE EVALUATION			
	# showing significant increase	**Total increasing scenarios**	**%**
Statistically significant increase (alpha=.05)	7	30	23
TEST FOR OVERALL SIGNIFICANCE			
	Without POD	**With POD**	
Mean (μ) accuracy rate	0.49	0.66	
Standard Deviation (σ)	0.11	0.11	
Median accuracy rates	0.50	0.66	
Independent samples t-test to compare means	t=6.00	p<0.0001	
Wilcoxon two-sample test to compare medians	z=4.74	p<0.0001	

The accuracy rates for this validity test were lower than those of previous validity studies, most likely due to the definition of accuracy being more difficult to achieve. The general trend was consistent with the other validity studies demonstrating lower accuracy rates for the higher heat release rates and longer duration simulations. Again, fire position 4 had the lowest accuracy rates. Both of the physical experiments increased in accuracy with the use of the POD. The ATF study had a statistically significant increase ($p<0.001$) in accuracy when using the POD (Fig 5-3).

The second validation test evaluated the distance between the centroid for the answer sets with the POD and without the POD as compared to the X- and Y-coordinate of the true origin (Fig 5-4 & 5-5). This test illustrated that 24 out of 32 (75%) of the scenarios where the POD was used resulted in a centroid closer to the true origin (Fig 5-4 & 5-5). The change of distance towards the true origin point was also plotted to illustrate the actual distance, positive indicating towards the true origin and negative indicating movement away from the true origin. Out of the 32 scenarios, 24 scenarios (75%) indicated movement towards the true origin, while 8 (25%) indicated movement away from the true origin [5].

A threshold of 11cm was identified as being a significant change in distance moved by the centroid of the answer set. The 11cm threshold represented the cell size for the FDS simulations. This was chosen, as it is a fraction of D* and essentially represents the resolution of the numerical experiments. D* for the 1.5MW fires was calculated to be 1.128 with a D*/dx of 10 or approximately 11.28cm, while the D* for the 4MW fire was calculated to be 1.67 with a D*/dx of 16 or approximately 10.44cm. The attempt with the simulations was to maintain the non-dimensional ratio of D*/dx to ensure that the fire resolution of the modeling simulations were similar. Using this threshold for significance, it was found that 21 out of 32 (~66%) scenarios had moved meaningful distances towards the origin, while 6 out of the 32 (18%) scenarios had moved meaningful distances away from the origin.

All centroid locations have been plotted for all fire positions for the simulations centered on (0,0) as the true origin (Fig 5-4). The centroid locations for the higher HRR, longer duration simulations can be compared to the lower HRR, shorter duration simulations for each fire position without and with the POD (Fig 5-4). In comparison, the higher HRR, longer durations were significantly greater in distances away from the true origin and were spread out further, indicating less reliability and validity. Finally, the centroid locations for the physical experiments have been plotted together and illustrate movement towards accuracy with the use of the POD (Fig 5-5).

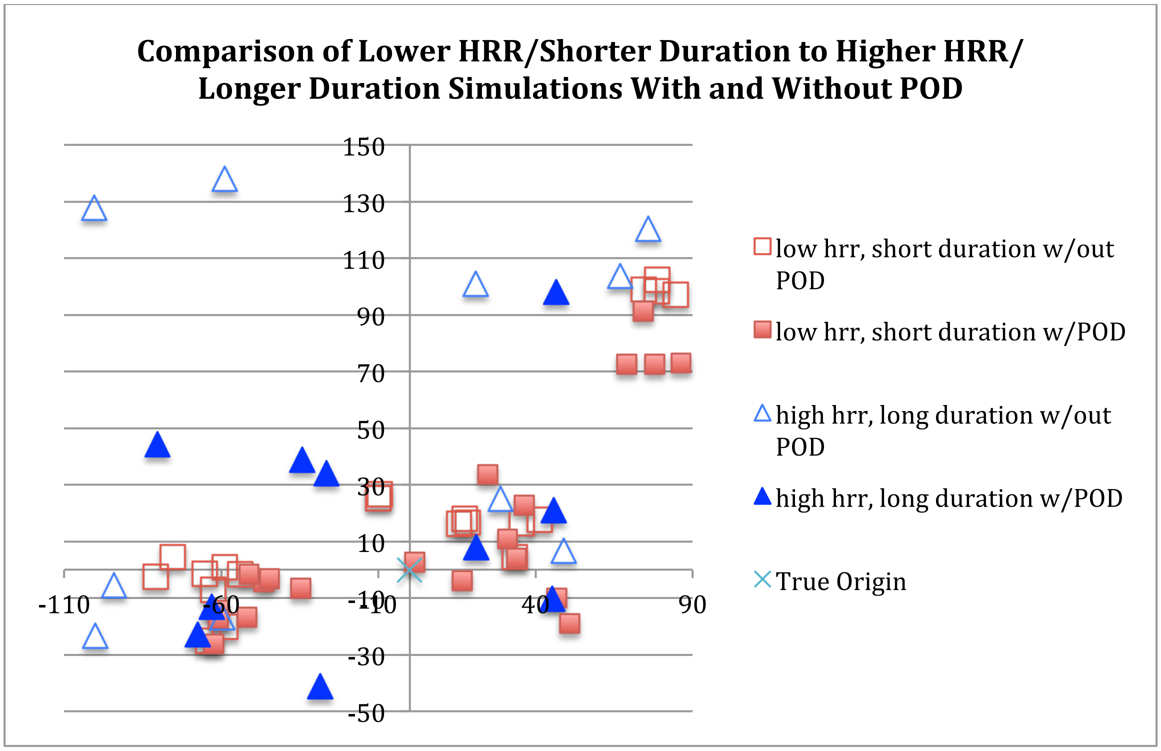


Fig 5-4: Centroid locations distinguishing between low HRR, shorter duration and high HRR, longer duration scenarios for all simulations and all fire positions (Note- The plot has been color-coded to easily distinguish between without and with the POD)

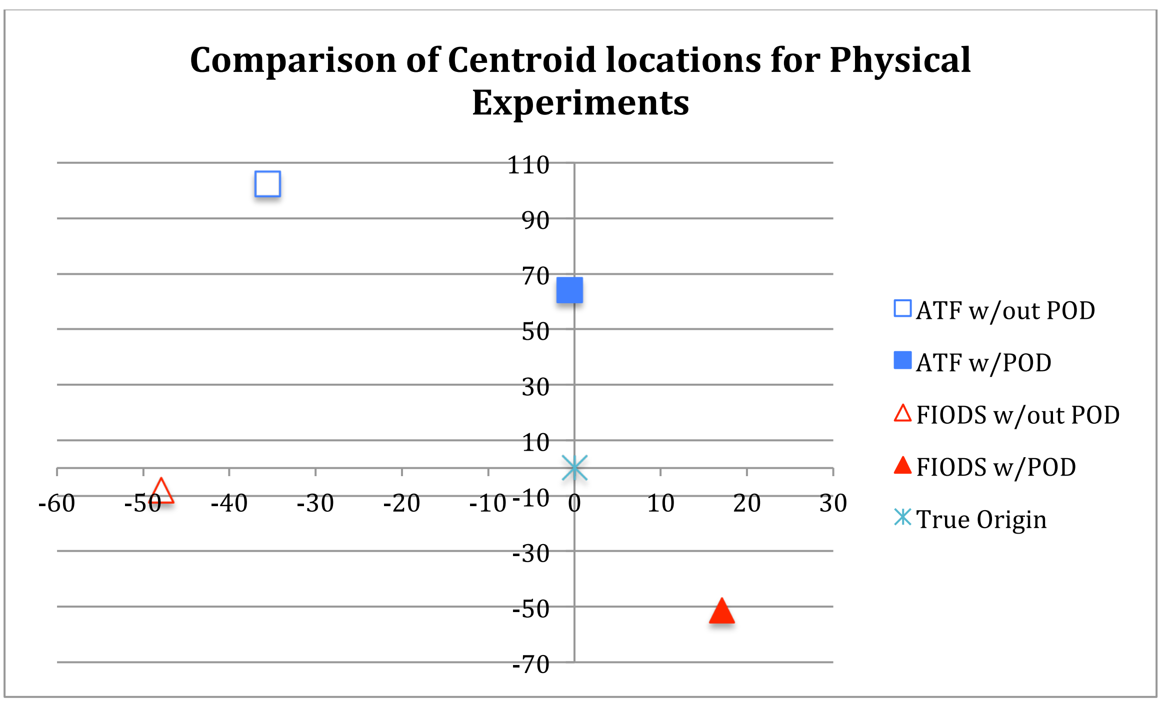


Fig 5-5: Comparison of Centroid Locations for Physical Experiments Without and With the POD

5.3 Evaluation of the Effects of Using Contents

Estimates evaluating the consequences of using content data versus not using content data were found to be unstable. The stratified analysis on contents versus no contents led to small sample sizes (*n=15*), which could give results more likely to be inconclusive, statistically insignificant, and strongly influenced by outliers. After further review in evaluating this question, it was also determined that the value placed on this analysis would be small if any due to the lack of directions within the proposed process on how to account for the content data. This is an area proposed for future research.

6.0 Conclusions

It has been shown through the use of reliability and validity tests that the proposed POD assisted decision makers in more consistently and more accurately determining the area of origin for a fire over a variety of scenarios.

6.1 Simulations

It was illustrated that the higher heat release rate, longer duration simulations consistently had lower accuracy rates and greater variability in answers both without and with the POD. This was expected based on a review of the literature. Remarkably, however, the greatest improvement in accuracy with the POD was demonstrated under these higher HRR, longer duration scenarios. This indicates that when participants use a systematic approach, their performance will improve significantly under the more difficult scenarios.

One of the most important aspects in evaluating origin determination is the ability for a decision maker to narrow the area of origin to the smallest area that still encompasses the true origin. This narrowing down to a smaller area, ultimately limits the area that requires in depth analysis for potential ignition sources. Therefore, the most important measures evaluated in this study were the ability of the decision maker to identify an area that encompassed the true region of origin. The POD performed statistically significantly better at identifying the true region of origin and the center point of origin. In addition to this, the POD illustrated lower variability across regions selected by the participants, which indicates that the decision maker was able to narrow their focus more when using the POD. In each of the scenarios where variability stayed approximately the same or increased, a handful of significant outliers were identified. Despite these outliers, the vast majority of the answers were identified as moving closer to the true origin. Some areas that may require further evaluation in these regards are refining the POD instructions and training on the use of the POD. It may also indicate that the decision maker should increase their hypothetical area of origin to encompass the entire compartment when higher HRR, longer duration fires are being investigated due to the increase in uncertainty.

The greatest variability and lowest accuracy rates with the simulations was found to be fire position 4 (near wall fire). This was also expected due to the lack of any wall surface near the origin to clearly characterize the plume-generated fire pattern associated with a possible origin. Additionally, the region for fire position four was not as clearly delineated as that for the other fire positions, which could have attributed to the greater variability in region selection. The use of the POD for this scenario did show a significant increase in accuracy and decrease in variability with the answers provided, which indicates that the POD assists the decision maker under this more difficult scenario.

6.2 Physical Experiments

The FIODS study reports an accuracy rate for approximately 600 professional fire investigators to be around 77% [19]. The variability decreased significantly when the POD was used in the FIODS scenario (Fig 11). The accuracy measures indicated that the participants without the POD were approximately 53%, but was increased to 83% when the participants used the POD.

The ATF study [17-19] reported an accuracy rate for selecting the quadrant of the room for approximately 60 professional fire investigators to be 5.7%. The accuracy measures indicated that the participants without the POD were approximately 6% accurate, but increased to 93% when the POD was used. The variability also decreased when the participants used the POD (Fig 11).

The accuracy and reliability for the participants when applying the POD to physical experiments was consistently demonstrated to increase in accuracy and decrease in variability with the use of the POD. Both physical experiments evaluated indicated similar accuracy rates to the reported literature when the novices did not use the POD. However, when novices used the POD, they achieved higher accuracy rates than the professional fire investigators given the same scenario.

6.3 Practical Implications

Origin determination through the use of fire damage involves a complex reasoning process, which can have significant uncertainty, consisting of a series of sub-processes that need to be coordinated and analyzed during a fire investigation. It is a gross oversimplification to state that the scientific method, by itself, provides the necessary guidelines to assist an investigator in determining the origin of a fire. Especially when qualitative analyses and potential biases can potentially influence the decision maker. Specific processes must be developed and tested for reliability and validity as outlined by the NAS recommendations [4]. The POD was developed to serve as a starting point to meet this requirement.

The POD simply identifies a systematic approach where many of the steps use well-accepted knowledge within the profession to illustrate the effectiveness of methodically evaluating damage in the context of the compartment fire dynamics. The POD assists the decision maker by removing much of the potential bias and qualitative interpretation, as well as providing a means of treating the associated uncertainty. Reliability and validity testing of the POD illustrates its effectiveness to bring novices to greater levels of accuracy in comparison to the professional fire investigation community. This research illustrates that anyone can use the POD and apply these seven steps with this knowledge and arrive at a better outcome. Thus, illustrating the effectiveness of the POD to satisfy much of the requirements identified in the NAS report [4].

Frequently, the overall goal of fire identification is to determine the cause of the fire. It is axiomatic that in order to find the actual cause, an accurate area of origin is required. Therefore, improving the area of origin determination should improve the ultimate cause determination.

6.4 Future Work

The value of content data, identification of the third dimension for origin determination (elevation), multiple origins, larger compartments, multiple compartments, and a variety of ventilation changes (i.e. multiple ventilation openings, sizes, shapes, elevation, wind direction and velocities) are areas that require further evaluation. Independent tests should be conducted for validity and reliability for each step within the proposed POD to better evaluate any sources of error.

Incorporation of the POD into easy to apply tools, including checklist type forms for use on scene, supported by a software-based system that can be run in the laboratory or office.

Finally, users should demonstrate their ability to employ processes in a scenario through proficiency testing. Proficiency tests should be developed in coordination with training programs.

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APPENDIX A – ISFI 2010 Conference Paper

DEVELOPMENT AND ASSESSMENT OF A DECISION SUPPORT FRAMEWORK FOR ENHANCING THE FORENSIC ANALYSIS AND INTERPRETATION OF FIRE PATTERNS

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A.1.0 INTRODUCTION

This plenary paper functions as a white paper that is intended to argue a potential solution to a problem. This paper identifies a research problem, the current approach to solving such a problem, and a potential process for using fundamental decision analysis coupled with fire protection engineering knowledge to solve this problem. It is not intended to specifically identify all of the variables that affect this problem or to solve the problem. Instead, this paper will suggest processes to approach this problem and to identify variables for further study.

A.2.0 RESEARCH PROBLEM

Forensic science is defined as the application of a broad spectrum of sciences to answer questions of interest to a legal system, including both criminal and civil actions (Houck & Siegel, 2006). The job of a forensic scientist is to provide scientific evidence, notably the analysis of forensic data, to the criminal justice system in order to reduce uncertainty (Taroni, et. al, 2010). However, in the real world, scientific evidence is always incomplete to some degree, which means there is a measure of uncertainty associated within each analysis. Consequently, the forensic scientist must interpret and present the significance of the evidence to the court of law. This is summarized best in the following exchange:

> Evidence does not say anything in itself; its significance needs to be elucidated in the light of competing propositions and background knowledge about the case at hand. There is a great practical necessity for forensic scientists to advise their clients, be they lawyers, prosecutors, jurors or decision makers at large, of the significance of their findings. Forensic scientists are required to qualify and, where possible,

> quantify their states of knowledge and to be consultants in the assessment of uncertainties associated with the inferences that may be drawn from forensic evidence (Taroni, et. al, 2006).

All forensic sciences are plagued by an inherent level of uncertainty associated with them. Fire and arson investigation is possibly one of the more complicated facets of the forensic sciences, because as a fire burns, evidence is continuously altered or destroyed.

A.2.1 Fire Investigation

Investigation of a fire incident is an integral part of the total fire safety model, including fire prevention and protection for a community. Fire investigation plays a critical role in identifying potentially faulty or improperly designed and installed products that may have played a role in the fire, and in identifying persons that deliberately started a fire with malicious intent. In the end, proper fire investigation should determine the fire cause, the cause of the resulting property damage, and most importantly, the cause of bodily injury or loss of life to civilians and firefighters. To meet this objective, an accurate cause assessment is essential, and an accurate cause assessment depends on a correct origin determination. Therefore, correct identification of the origin of the fire is the scene investigator's most important hypothesis.

A.2.1.1 Use of Fire Burn Pattern Data to Identify Area of Fire Origin: Current Practice

Since the beginning of organized fire investigation in the late 1940's, fire investigators have relied on fire burn patterns as their basis for determining the fire origin (Rethoret, 1945). Fire patterns are defined as the "visible or measurable physical changes, or identifiable shapes, formed by a fire effect or group of fire effects" (NFPA 921, 2008, p. 12). Absent the testimony of reliable eyewitnesses to the fire's inception, the investigator is required to determine the origin by observation and expert interpretation of the physical evidence (fire patterns) in an attempt to reconstruct the fire. As such, fire origin determination is largely a matter of fire pattern recognition and analysis (NFPA 921, 2008).

Currently, fire investigators identify fire patterns by visible observation or through depth measurements of materials affected by fire. This analysis demands the coupling of the physical laws of fire dynamics with the investigator's inference regarding the damage. The pattern data is collected and then analyzed by the investigator and is assigned some weight or meaning comparative to all of the remaining damage within the compartment. The investigator attempts to identify the area(s) of damage that can best explain the collected data to arrive at a decision regarding the area of origin. In other words, the analysis of fire patterns involves identifying damage and then performing a comparative analysis to other materials and damage observed.

Presently, much of this analysis is implicit and subject to investigator bias, with assignment of weights to patterns being largely dependent on the investigator's knowledge, experience, education, training, and skill, without the benefit of a structured framework to help guide the investigator through the process. This is of particular concern with respect to the importance of being able to identify and properly weigh potentially subtle differences from one fire scene to the next, some of which could have significant bearing on the interpretation of the evidence. The analysis is also limited to the investigator's personal knowledge and limitations.

In part, this is due to the nature of fire itself. Fire is defined as "a rapid oxidation process, which is a chemical reaction resulting in the evolution of heat and light in varying intensities" (NFPA 921, 2008). To be able to discern the subtleties of one situation to the next; of small differences in fuel package or location, compartment geometry, or ventilation openings, the investigator must have a solid foundation of the physical laws that govern fire behavior, and how the factors interrelate, in order to make the best decision possible. The most effective fire investigators will compare the observed damage to attributes associated with the physics and thermal sciences of enclosure fire dynamics.

However, not all fire investigators have the same level of education and training, or appreciation for the interaction of the fire in its environment. Historically, fire investigators have been individuals without any formal education or training in scientific methodology. In a recent survey of 422 fire investigators by the National Center for Forensic Sciences, findings revealed that only 33% held a college degree, of which only 10% were related to science or engineering (Minnich, n.d.). This survey also related that the average fire investigator has only received 60 hours of training, indicating a one-to-two week course. This suggests that many investigators have received the majority of their training through informal on-the-job training. More experienced fire investigators would mentor less experienced fire investigators, unfortunately in some cases, passing on what has since become realized as a collection of myths (NFPA 921, 2008). This occurred because many investigators, particularly those who obtained their "basic training" before 1992, were trained with misinformation and misconceptions, as they lacked the fire science understanding to help them make better interpretations of the information available to them (Lentini, 2006). A number of those investigators have taken very little additional training since then, and of those, some do not recognize how flawed their early training was or the impact of how the lack of training regarding current techniques affect the assessments that they make. The most recent example of this failure being the execution of Cameron Todd Willingham by the State of Texas on the basis of an investigation that relied on "poor understandings of fire science and investigators that failed to acknowledge or apply the contemporaneous understanding of the limitations of fire indicators" (Beyler, 2009).

The standard of care in the fire investigation profession is the 2008 edition of the National Fire Code NFPA 921 *Guide for Fire and Explosion Investigations*, as espoused by the National Fire Protection Association (NFPA). Since its inception in 1992, NFPA 921 represents the industry "standard of care" for fire and explosion investigations. With the introduction of NFPA 921, the fire investigation profession began a movement toward the implementation of science-based principles in fire investigation. Although a good step forward, this change has sometimes been met with fierce resistance, and only since 2000 has the scientific method become "generally accepted" by the relevant community. This text reaffirms the importance of fire patterns and their analysis as the means to determine an area of origin. A process to help step fire investigators through their analysis in a scientific manner remains unaddressed.

Even though historic and current treatises espouse the use of fire patterns for fire investigations, only limited research has been conducted to study the scientific foundation of fire patterns. The National Institute of Standards and Technology (NIST), National Institute of Justice (NIJ), and the United States Fire Administration (USFA) have completed full-scale fire research specifically to address fire patterns (McGarry, 1997; Gottuk, 2009;

Shanley, 1997). Due to the numerous parameters associated with full-scale fire tests and the limited number of studies conducted, there are still many questions unanswered.

The legal and science professions are currently scrutinizing forensic science, which is forcing the nation to question the discipline's scientific foundation (NIJ, 2009). Recently, the National Academy of Sciences released a cautionary report regarding this type of analysis (2009). In this document, the authors outlined the need to improve the scientific foundations of the forensic disciplines, particularly those that are dependent on qualitative analyses and expert interpretation of observed patterns, including fire investigations (NIJ, 2009).

When lacking a systematic approach to solving complex problems, many professions have turned to decision support frameworks, tools or methods, the intent of which are to guide the decision by asking questions and helping to assess the weight or importance of variables. It is evident that with the education and training for the average fire investigator often lacking helpful scientific and engineering knowledge, coupled with the lack of a systematic procedure for the analysis of fire patterns, a major gap exists within the fire investigation profession. A science-based decision framework is proposed to fill this gap within the profession. From a scientific basis, an investigator who includes attributes of fire dynamics in the evaluation of fire patterns is more likely to reach a technically valid determination of the origin and cause of a fire. It is recognized, however, that not all fire investigators in the near future will receive the necessary training and education to address their knowledge gaps, and even if they do, without guidelines they can use in the field to help them do a better job, it will be difficult to apply newfound knowledge.

A.2.2 Use of Decision-Support Frameworks to Enhance Decision-Making under Uncertainty

In the face of non-systematized approaches to solving complex problems, many professions have turned to decision support frameworks, tools or methods. As used here, decision frameworks, tools or methods encompass any mechanism used to support the systematic identification and assessment of information deemed important to a decision, ranging from checklists, to structured problem-diagnostic tools such as fault trees, event trees or decision trees, to computationally supported decision analysis tools. Decision support frameworks are derived from the field of decision analysis, as well as from uncertainty analysis and risk analysis.

Decision analysis has its roots in operations research, where it emerged from a desire to better understand and address decision-making under uncertainty, becoming viewed as a unique area of study in the 1960s (Howard, 1966; Raiffa, 1968). A fundamental principle of decision analysis is that people do not always have all the data or information needed to make a good decision, and sometimes do not know where to go to obtain the information, or how to judge the value of the information to the overall decision. As these areas began to be studied, approaches began to be developed to help individuals and organizations identify the components of a good decision, how to structure the decision problem, and how to treat the associated uncertainty (e.g., Kahneman and Tversky, 1974; Von Winterfeldt and Edwards, 1986; Morgan and Henrion, 1990; Kleindorfer et al., 1993; Clemen and Reilly, 2001; Donegan, 2008).

Key aspects of a decision support framework include identification of decision objectives (e.g., identify the most likely factors leading to presence of a particular burn pattern), attributes (criteria) which are important to the decision problem (e.g., fuel type and location, compartment geometry, ventilation openings, etc), and the weighting (importance) of the attributes to the decision given the uncertainty and variability in the data and relationship between attributes. Once these parameters are identified and agreed, various techniques can be applied to facilitate collection of critical information, analysis of the data, and facilitation of a decision.

This type of structured approach to reaching better decisions has been applied in various fields, from business and economic decisions (e.g, Clemon and Reilly, 2001), to building and fire safety analysis and regulation (Meacham, 2000; Donegan, 2008), diagnostic support within the psychological, psychiatric, and medical professions (Boorse, 1976; DSM-IV-TR, 2000), failure analysis (Benner, 1975; Ericson, 1999; Vesely, 1981) and forensic analysis (Taroni, et. al, 2005; 2010; Morvan, 2007; Jarman et al., 2008), including with respect to fire investigation (Biedermann, A., et. al, 2004).

A.2.3 Decision-Support Framework to Increase Reliability of Burn Pattern Interpretation

It is evident that with the education and training for the average fire investigator often lacking helpful scientific and engineering knowledge, coupled with the lack of a systematic procedure for the analysis of fire patterns, a major gap exists within the fire investigation profession. A science-based decision framework is needed to fill this gap within the profession. From a scientific basis, an investigator who includes attributes of compartment fire dynamics in the evaluation of fire patterns is more likely to reach a technically valid determination of the origin and cause of a fire. It is recognized, however, that not all fire investigators in the near future will receive the necessary training and education to address their knowledge gaps, and even if they do, without guidelines they can use in the field to help them do a better job, it will be difficult to consistently apply newfound knowledge. As an additional benefit, the decision support data can be updated from time-to-time so that even knowledgeable investigators can be brought up-to-date with the most current research.

A.2.4 Goals and Objectives

The goal of this research is to develop and implement into practice a decision support framework that will assist forensic fire investigators in assessing the efficacy of fire burn patterns as reliable indicators of the area of fire origin. The framework will be based on identifying, relating and weighting key attributes of the fire environment, observed and measured, from a compartment fire dynamics and related fire physics and chemistry basis, with the aim to facilitate more reliable evaluation of visible and measurable fire patterns given the influence of the fire dynamics attributes. Ultimately this framework will guide the investigator in gathering on-scene evidence that can better assist in the scientific analysis of the area of origin hypothesis, and will allow the user to identify and evaluate the most common attributes that affect the pattern reliability based on information and research studies that are currently available.

Procedurally, the proposed framework will first provide the investigator with a series of research-based evidentiary attributes, which have been shown to affect the reliability of that pattern, about which data will be collected at the scene. The framework will then provide the investigator with the basis for a qualitative assessment of the reliability of that pattern, given the strength of the attributes, and help the investigator assign a more appropriate confidence weighting to the specific pattern. The decision support framework will also help to assess the scientific probability of each pattern occurring, given the evidentiary data, providing quantifiable measures of the reliability as well. Ultimately, the combination of pattern evidence, given the identified attributes, their reliability measure and respective weighting will provide a more objective and technically valid means to arrive at an area of origin.

This framework will also assist with the evaluation of multiple origin hypotheses by analyzing each fire pattern in support and in opposition to the various hypothetical area(s) of origin. Consequently, this framework would also identify areas that require further study that would allow the framework to be compressible and/or expandable based on the findings of each research study. As the state of the art develops, this framework will also identify other tools (e.g., computer fire models) that can be used within the framework to better assess the area of origin objective.

A.3.0 Literature Review

The following literature review has been divided into two sections, (1) studies that have been conducted to help identify fire patterns in compartment fires, and (2) studies that provide evidence of the effectiveness of decision support frameworks in other professions.

A.3.1 Fire Pattern Studies

As early as 1945 Rethoret in his text *Fire Investigations* explained: "In which direction is the wood carbonized? Study closely the depth of carbonization at various places. Bear in mind that superheated gases spread upwards. This again will assist you in getting back to the point of origin." (p 36)

The Law Enforcement Assistance Administration collected some of the myths about fire investigation in a 1977 study entitled "Arson and Arson Investigation: Survey and Assessment" (Boudreau, Kwan, Faragher & Denault). The arson investigators surveyed cited interpretation of "burn indicators" as the most common method of establishing arson. Some of the burn indicators used were alligatoring, crazing of glass, depth of char, lines of demarcation, sagged furniture springs and spalled concrete. The LEAA report, after listing the indicators, provided the following caution:

> "It is recommended that a program…be conducted to establish the reliability of currently used burn indicators. Of particular importance is the discovery of any circumstances, which cause them to give false indications (of, say, a fire accelerant). A primary objective of this testing would be to avert the formidable repercussions of court ruling on the inadmissibility of burn indicators on the grounds that their scientific validity had not been established. In addition, the research might well uncover new methods of value to fire and arson investigators" (Boudreau, Kwan, Faragher & Denault, 1977).

Given the history of using fire spread and fire pattern analysis, it was reasonable that the system would also be included in the first edition (1992), and all subsequent editions of NFPA 921 *Guide for Fire and Explosion Investigations.* In the 2008 edition of NFPA 921 the importance of fire patterns is clearly reiterated by stating that "the major objective of any fire scene examination is to collect data as required by the scientific method (*see 4.3.3*). Such data include the patterns produced by the fire" (Section 6.1.1).

In 1994/1995 The United States Fire Administration, in conjunction with the National Institute of Science and Technology, Building and Fire Research Laboratory (NIST-BFRL) launched the fire pattern research committee and produced the USFA Fire Pattern Test report, authored by Shanley, July 1997. This project consisted of 10 separate full-scale burns to produce the first scientifically controlled and recorded research into the formation, growth, and investigation of patterns produced in fires. These tests produced the first data that supported fire patterns as being useful in fire investigation. However, this report also demonstrated that in two tests, "distinctive patterns were produced which without careful study and a full understanding of *all factors* which influenced the progress and growth of the fire, could easily be interpreted to indicate incorrect or multiple origins" (p. 56). This study also noted that ventilation was one of the most misunderstood variables, having the influence to alter "normal" fire pattern production.

In March of 1997, McGarry and Hill, in conjunction with the University of Maryland, continued the full-scale room experiments. Four full-size furnished bedrooms were burned at the University of Maryland Fire Rescue Institute Facilities. The burns were intended to be identical to determine if differences would be discovered with a close analysis of the results. In both cases, ignition of a gasoline spill next to an upholstered chair was used to initiate the fire. The researchers noted differences, and attributed these to small variations in the inflow of air.

Another series of full-scale fire tests was conducted with funding provided by the National Institute of Justice, resulting in a report "Full Scale Room Burn Pattern Study," released in December 1997 (Putorti). Putorti reports that "comparisons of the conditions of the rooms and furnishings after the experiments resulted in the determination of several similarities, as well as many differences, between experiments with the same method of ignition" (p. 26). He attributes the differences to the "ventilation effects" (p. 26).

In 2002, fire pattern analysis was identified as an essential area of research by the National Fire Protection Association's Fire Protection Research Foundation. In their report, authored by its "Research Council on Post-Fire Investigation", they recommended that "if patterns are to be used for origin and cause determination, forensic methods to identify the specific source of a pattern need to be developed and rigorously vetted" (p.5).

Beginning in March of 2005, a series of twenty full-scale fire pattern studies were conducted by Eastern Kentucky University and the National Association of Fire Investigators (Gorbett, et al., 2006; Hopkins, 2007; Hopkins, 2008; Gorbett, 2010). These studies were completed using the EKU's Fire and Safety Engineering Technology burn facility. The test fires were conducted in identically constructed, finished, and furnished living room and bedroom compartments. These studies focused on fire patterns reproducibility, patterns persistence through flashover, the use of fire patterns in origin determination, and the influence on fire patterns produced by an initial, low heat release rate fuel. The most important finding from these tests is that "the interpretation of *all* fire effects provides substantial evidence for the investigator to identify the correct area of origin" (Gorbett, 2010).

Between 2006 and 2008 (Hicks, et al.), a fire pattern reproducibility study using single fuel items was completed at Eastern Kentucky University. Forty-eight tests were conducted with a standardized ANSI/UL wood crib and ten additional tests were conducted with commercially available polyurethane foam recliners. These two studies resulted in fifty eight single fuel items burned and fire patterns documented. The studies demonstrated that class-A fuel items and composite materials would reliably reproduce similar fire patterns from a single fuel burning.

In 2005 and 2008 (Carman, 2009), three studies were completed in conjunction with a training seminar to analyze burn pattern development in post-flashover fires. This study focused on the impact of ventilation on fire patterns and the ability of fire investigators to use fire patterns to determine the origin area. Carman (2008 & 2009) divided the room into four quadrants and performed a survey of the attendees in an attempt to derive an error rate study of investigators. He reports a 5.7% success rate of determining the correct quadrant where the fire was started. Neither study provided the demographics of the attendees, nor could it provide any statistical rigor. Nevertheless, Carman attributed the failure to the lack of understanding by the investigation profession of the differences between pre- and post-flashover fire behavior.

In 2009 (Wolfe, Mealy, and Gottuk), through the funding of NIJ, fifteen full-scale fires were conducted with varying ventilation conditions and fuels. They focused on unventilated fires, the fire growth associated with these types of fires, and their forensic analysis. While much of the research was based more on the tenability limits and associated dynamics in unventilated fires, they reported on a few forensic-based conclusions. These included that soot deposition can be used to aid in the area of origin determination and that the clean burn area size is proportional to the fire size (2009).

A.3.2 Decision Support Frameworks, Tools and Methods

As introduced earlier, decision frameworks have been applied to a diverse set of decision problems across a wide range of professional disciplines to help facilitate better decisions under uncertainty. The first major application of decision analysis to complex problems was the development of military strategies during World War II, known as operations research (Clemen and Reilly, 2001), emerging as a recognized discipline in the 1960's (e.g., Howard, 1966; Raiffa, 1968), and in combination with related tools, such as uncertainty analysis, risk analysis and failure analysis, soon found application in areas related to forensic investigation.

As early as the mid 1960s, the application of decision analytic techniques, coupled with structured diagnostic techniques, such as fault tree analysis (FTA), event tree analysis (ETA), and failure modes and effects analysis (FMEA) began to be applied in the investigation of aircraft and nuclear power plant accidents (Rassmussen, 1975; Benner, 1975; Vesely, 1981; Ericson, 1999). Over time, these tools became embedded in the pre-construction risk analysis of aircraft, nuclear power plants, and other facilities (e.g., chemical and petroleum processing facilities (CCPS, 2002), buildings (e.g., Meacham and Johann, 2004; Watts, 2008; Meacham et al., 2008), critical infrastructure (Fenelon et al., 1994), as well as in failure analysis of systems and facilities (e.g., CCPS, 2002), and work to integrate these tools with decision analysis approaches continues (Puente et al., 2002).

In much the same way, decision analysis tools began to be used as diagnostic support tools within the psychological, psychiatric, and medical professions starting in the 1970s (Boorse, 1976; DSM-IV-TR, 2000). Over time, decision analysis tools have been applied to a wide range of diagnostic, failure and forensic analysis in the medical profession, including development of decision support tools for assessing heart failure (Hossen and Al-Ghunami, 2006; Colantonio et al., 2008), microbial forensics (Jarman et al., 2008), and forensic entomology (Morvan et al., 2006), and within forensic science in general (Taroni, et. al, 2005).

This trend continues, with newer decision support tools, such as Bayesian networks and probabilistic inference, being applied to forensic sciences (Taroni et al.; 2010), and even to fire investigation, where the application of this logic towards ignitable liquid residue has been investigated (Biedermann, A., et. al, 2004). These examples provide a glimpse of the breadth of successful application of these decision making techniques in diverse fields.

A.4.0 Research Design and Methods

Development of the decision framework will consist of three operations: system design, professional judgment review and critique, and systems testing.

A.4.1 System Design

The system design will consist of the following:

1. Analysis of the requirements of fire investigation standards and related authoritative treatises,
2. Analysis of the relevant literature regarding compartment fires, fire pattern studies, and decision analysis,
3. Organization of the results of this analysis into a decision support framework format that is suitable for identifying critical attributes, including fire scene data and information (observed and measured) and critical post-scene data or information (from testing, analysis or other), the relationships between attributes, and the weighting of the attributes based on relative importance to the decision given the data and associated uncertainty,
4. Elicitation of professional judgments on the weighting of the fundamental attributes relative to the area of origin determination objective (decision objective), and
5. Iterative incorporation of system changes resulting from the professional judgment review and system tests.

It is currently envisioned that the decision support framework will consist of two primary components: a simple to use data collection tool, which could be in checklist, tabular or similar format (field use), and a computational analysis tool, which takes input from the data collected and helps lead the user through a structured process of reaching a decision relative to the reliability of fire patterns as indicators of area of fire origin (office use). Research from this effort will underpin the analysis tool, including attributes, relationships and weighting, meaning that for the investigator, data collection and input into the tool will be their primary responsibilities.

A.4.2 Professional Judgment Review

Initially, a decision support framework will be developed based on the available literature and research studies, as well as the experience and professional judgment of the principal investigators and research assistant, as outlined above. Subsequently, a group of experts will be consulted, through the mechanism of a "Delphi" exercise, to test such factors as attribute relationship and weighting. The Delphi group will consist of practitioners/experts within the fire investigation profession. Various approaches to obtaining relevant information through a "Delphi" process will be explored. In-person and web-based approaches will be considered.

Delphi is a procedure for obtaining the most reliable consensus of opinion of a group recognized as experts on a technical question for which no "true" answer is within the state of current knowledge (Dalley, N, Helmer, D, 1963). The core of the process is that the question is considered independently by members of the group prior to committee work. The responses are tabulated and circulated to group members who revise their "answers" based on further thought and consideration of the collective response. Additional rounds of response possibly involving direct contact and discussion among the group members can ensue. In its classic form, Delphi incorporates various statistical measures of the "convergence" to consensus, which are circulated with the group along with the responses (Tesfamariam, S., Sadiq, R., Najjaran, H., 2010). In this proposal, a questionnaire provided to the group will focus on obtaining expert interpretation of the weighting associated with a given pattern based on the fire dynamics attributes.

A.4.3 System Testing

The testing will involve a series of exercises to determine the validity of the framework. The testing will assess: how users apply the framework based on what is postulated in this proposal; how well the framework operates in guiding decisions of practitioners and students during practical field exercises; and, the consistency of application and outcomes. These exercises will include:

(1) Examinations of previously published fire pattern studies with the framework;
(2) The framework will be tested via integration with practitioners in the field.
(3) Two phases of workshops (alpha and beta) with fire science students and fire investigation experts will be employed throughout the duration of the project.

A.4.4 Proposed Objectives and Attributes (Higher Level Framework)

Although research as outlined above is needed to complete development and assessment of the framework, some preliminary research has already been conducted to demonstrate how the approach is anticipated to develop. To date, effort has focused on the 'higher-level' issues that influence fire patterns. The following is a working list of the higher-level objectives and attributes that influence fire pattern identification and analysis. The lower-level, more specific attributes will be identified as part of this study through research and the "Delphi" group.

A.4.4.1 Fire Effects

The analyst observes damage in or on surface materials after a fire. The damage is commonly referred to as a fire effect by the fire investigation profession. Fire effects are defined as "the observable or measurable changes in or on a material as a result of exposure to the fire" (NFPA 921, 2008, p. 39). There are a total of 15 effects listed in NFPA 921 (2008) and will be the base list of observations (Table A-1).

The damage can be visible and/or measurable. The extent of this damage and type of damage will be dependent on the type of material and its associated factors (Figure A-1). Each fire effect will be processed through steps 4.4.1-4.4.4 to properly assign the factors that created the effect.

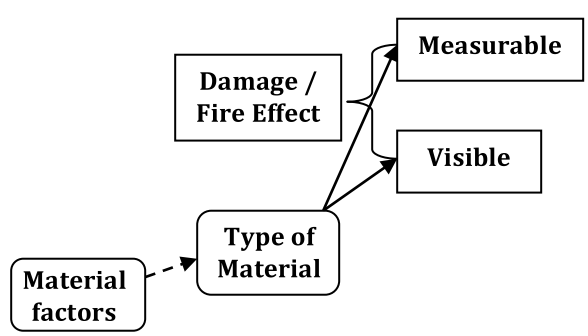

Figure A-1: Initial Observations

Table A-1: Base List of Fire Effects and Observations identified in NFPA 921 (2008)

FIRE EFFECT	OBSERVATION(S)	
	Visible	Measurable
Temperature Estimation	X	
Mass Loss	X	X
Char	X	X
Spalling	X	
Color Changes	X	
Melting of Materials	X	
Thermal Expansion and Deformation	X	X
Oxidation	X	
Deposition	X	
Clean Burn	X	
Calcination	X	X
Window Glass	X	
Furniture Springs	X	
Victim Injuries	X	
Light Bulbs	X	

A.4.4.1 (a) Material Factors

There are numerous factors that may influence how a material is affected by heat and exposure to incomplete combustion products (i.e. smoke, aerosols). The loss of mass from a material may also have several variables that are typically dependent on the material and the exposure to heating. A short list of material properties that may influence the effects of exposure of a material exposed to a fire environment, include: moisture content, thermal conductivity, density, specific heat, critical heat flux, ignition and flame spread propensity, and heat of gasification/vaporization.

A.4.4.2 Visible and/or Measurable Damage

The visible and/or measurable damage in or on a material is caused by one or a combination of the following: heat, deposition, and/or consumption (NFPA 921, 2008). The investigator may use this effect as an indicator to initially classify the cause of the observed damage (i.e. clean burn=heat). Next, the analysis of the following factors and their involvement into the cause of the damage must be considered: fire environment, compartment, fuel(s), and suppression (Figure A-2).

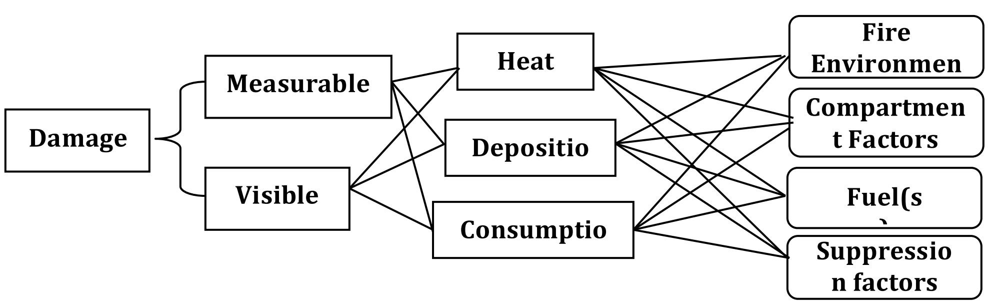

Figure A-2: Attributes that influence visible and measurable damage

A.4.4.3 Heat, Consumption, and Deposition

The visible and measurable fire patterns are listed in NFPA 921 to be caused by one or a combination of the following physical effects to the material: heat, deposition, and/or consumption (2008, p.48). Heat, consumption, and deposition will be separated into local or global effects that will assist analysts in better identifying the cause of the resulting damage. These physical effects will be broken into more specific attributes as part of this study, however, a brief listing has been provided below.

- *Heat* - heat transfer is driven by fundamental physical principles, including: temperature difference, view factor (radiant heat transfer), turbulent/laminar flows (convective heat transfer), thermal inertia (conductive heat transfer).
- *Consumption* – the loss of mass from a material when exposed to heat is considered consumption of the fuel or material. This is based on heat exposure and material properties.
- *Deposition* – Smoke contains particulates, liquid aerosols, and gases (NFPA 921, 2008). As smoke decreases in temperature and/or collides with cooler surfaces, deposition of the smoke occurs. Locations of protected areas, areas of greater and lesser soot deposition, and the effects of thermophoretic forces (temperature difference and velocity between hot gas layer and cooler wall surfaces) will be assessed. The differences between horizontal and vertical surfaces will also be noted and referenced as to their relative importance.

A.4.4.4 Fire Dynamics Attributes

A fire can develop in many different ways, which may significantly influence the resulting damage. The major attributes that influence fire behavior have initially been divided into 4 categories based on their relative importance to the developing fire and the resulting impact on the location and degree of damage. The initial portion of this proposal will focus specifically on breaking these categories into detailed attributes, however, a brief listing is provided below.

A.4.4.4 (a) Fire Environment

The first priority is to determine what environment existed during the fire. This will be accomplished by analyzing the resulting damage to determine if the fire was ventilation-controlled or fuel-controlled. Additionally, this analysis would take into consideration if the compartment reached full room involvement or not.

A.4.4.4 (b) Fuel (Location, Heat release rate, number of fuel items)

Secondly, the fuel items will need to be identified, including the heat release rate(s), the location of the fuel in proximity to other fuel items, the presence of multiple fuels, and the configuration and orientation of the fuel items. Finally, a comparative analysis will be undertaken between each fuel item to identify their relative involvement in the damage.

A.4.4.4 (c) Compartment Factors

Basic compartment factors may influence the development of a fire, therefore, the area, volume, configuration, and ceiling heights of compartments will need to be assessed as to their relative importance to the damage observed. Additionally, the location of damage in the compartment may provide the investigator with valuable data regarding the fire environment. One of the most important factors that will be assessed under compartment factors is the location, number, and position of the ventilation openings for the compartment. Finally, the adjoining space or compartment volume will be assessed to determine the availability of "fresh" air and the presence/lack of wind.

A.4.4.4 (d) Suppression Factors

The suppression factors that will be assessed as to their impact on visible and measurable damage includes the location of water application, duration of fire burning prior to arrival, duration required to extinguish the fire, location of fire department entry, method of extinguishment, use of positive pressure ventilation (i.e. forced convection, mechanical movement of smoke (deposition of products) or spreading of contaminants), and the change of ventilation upon arrival (breaking windows, opening doors, cutting holes in ceiling).

A. 4.4.5 Grouping of Fire Effects

Each effect will be processed through the analysis of the fire dynamics attributes from above in an attempt to group like effects. Once groups of effects have been identified with similar causes, then a decision can be made regarding the basis for pattern generation. NFPA 921 (2008) provides the following classifications for the generation of fire patterns: ventilation, plume, suppression, upper layer, full room involvement (Figure A-3).

Comparative analysis of the damage (greater/lesser) may provide the analyst with data that provide indicators (fire patterns) of intensity, fire travel, and/or geometry. However, if the damage cannot be determined conclusively, then a determination of insufficient data is appropriate.

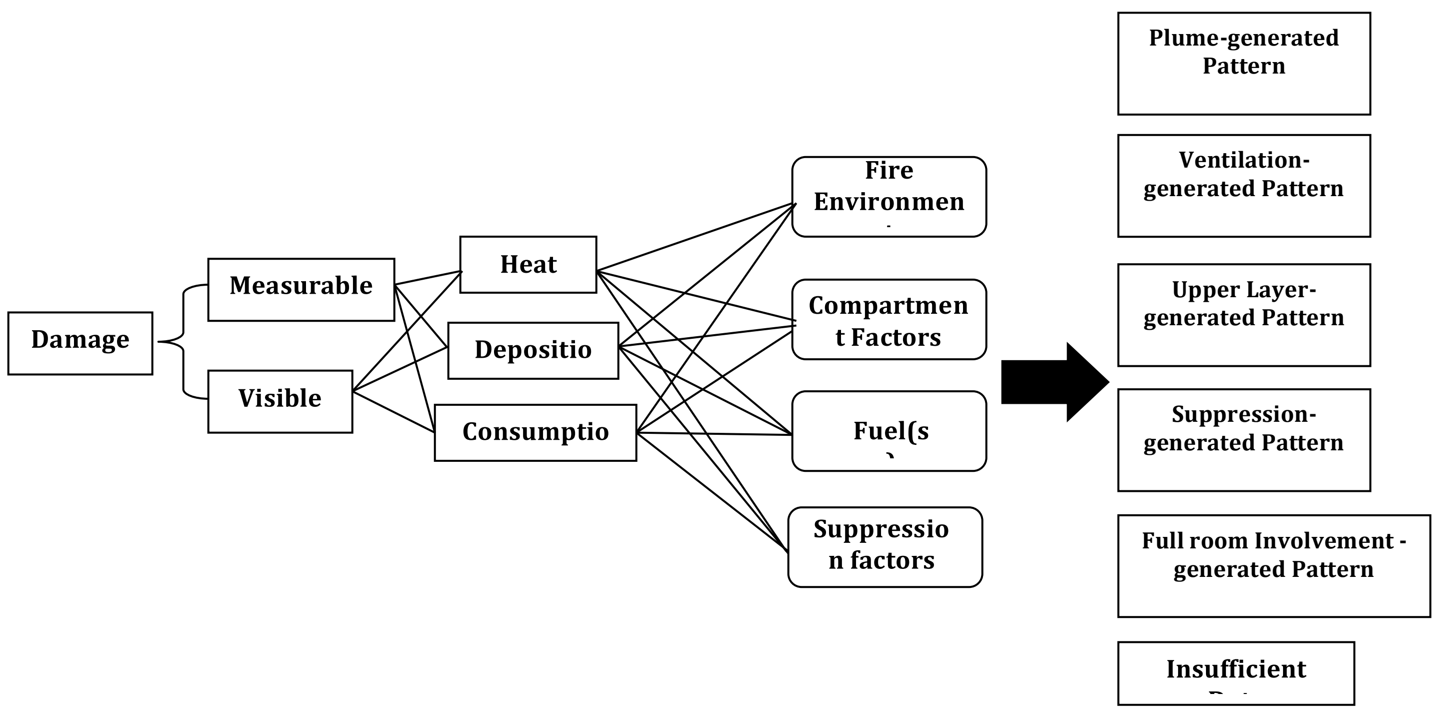

Figure A-3: Grouping of Effects

A.4.4.6 Analyze all Collected Fire Effects Data: Fire Pattern Analysis

When the cause of the damage has been established, then the fire effect may provide the analyst a direction of fire travel or a location of more intense burning/longer burning duration (Figure A-4). Analysis of fire patterns involves the processing all of the collected data and determining if there is a preponderance of the patterns/damage in an area or areas.

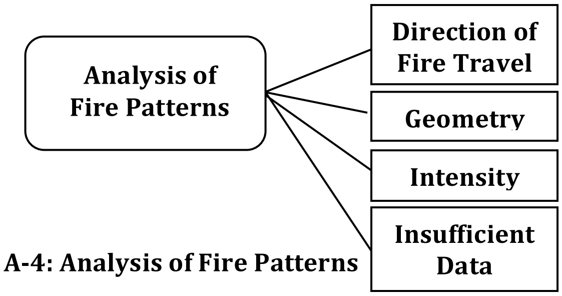

Figure A-4: Analysis of Fire Patterns

A.4.4.7 Determining the Area of Origin

Arrival at a hypothetical area of origin requires the analyst to test the hypothesis by asking several questions: (1) is an ignition source present or not present? (2) Was a fuel package present or not? (3) Is the actual damage observed consistent with expected damage based on first fuel ignited and fire growth? (4) Is the ignition source competent compared to the first fuel ignited? (5) Can the first fuel ignited result in the fire spread scenario that resulted in the damage observed? (6) Are there more than one hypothetical areas of origin? Ideally, the investigator would strive to use this system to arrive at an area of origin of a practicable size, which will be defined here as the first fuel ignited (Figure A-5).

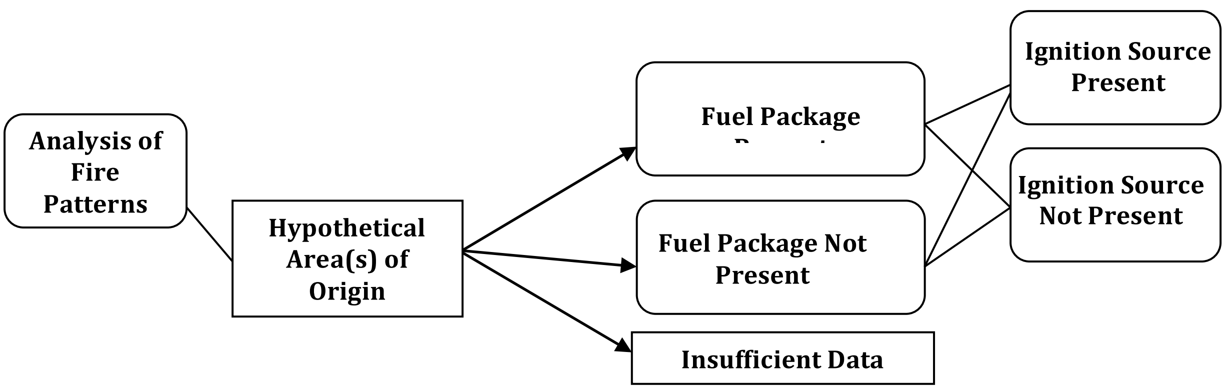

Figure A-5: Area of Origin Hypothesis

A.4.4.8 Insufficient Data

Insufficient data requires the analyst to collect more data, reanalyze the data, retest, and rework the process. However, if insufficient data still exists, then the area of origin is undetermined.

A.4.4.9 Total Process

At this point, the resultant fire patterns and the corresponding fire dynamics attributes will be assessed with one of the statistical methods (Figure A-6). This will provide the investigator with a probability for each fire pattern and its resultant reliability, as well as a quantifiable measure of reliability for the process. The specific statistical method will be determined throughout the implementation of this study.

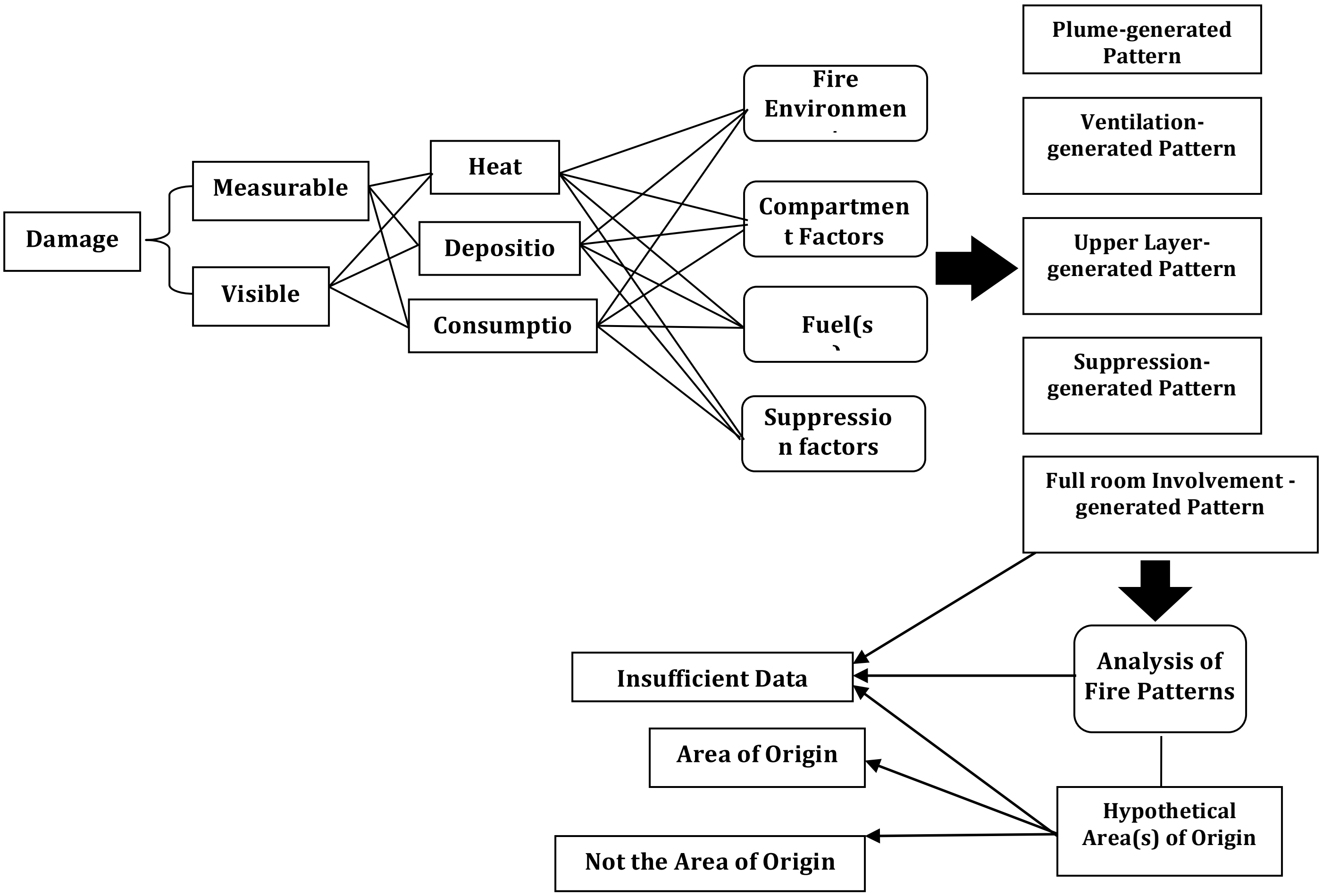

Figure A-6: Total Process

At the culmination of the project, a computer system based on the decision framework will be developed that allows investigators to make a better origin decision. An investigative form will be developed to assist with on-scene data collection, similar to a checklist, which will assist the investigator in considering the appropriate attributes and resultant effects.

A.5.0 Conclusions

As fire patterns are the cornerstone of origin determination, and fire investigation altogether, it is necessary to equip investigators with tools to help them conduct better and more scientifically-supported investigations. This is especially important where there are a range of visual and measurable data that interrelate in different ways to impact the reliability of fire patterns as indicators of the origin area. To help advance fire investigation and the integration of science and the scientific method into the process, a better, more systematic, research-based decision support framework for determining an area of origin based on fire patterns will be developed. The proposed research will enhance the current methodologies prescribed and utilized in the fire investigation community. The natural variability of fire patterns and damage characteristics will be determined and disseminated to the fire investigation and legal communities. The scientific underpinnings for these fire patterns will be determined to assist fire investigators in correctly interpreting fire damage and assigning more appropriate weighting to fire patterns based on the fire dynamics attributes.

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Appendix B – DOFD JFS Paper

A New Method for the Characterization of the Degree of Fire Damage to Gypsum Wallboard for Use in Fire Investigations

ABSTRACT:
A new method to characterize the degree of fire damage to gypsum wallboard is introduced, implemented, and tested to determine the efficacy of its application among novices. The method was evaluated by comparing degree of fire damage assessments of novices with and without the method. Thirty-nine "novice" raters assessed damage to a gypsum wallboard surface, completing 66 ratings, first without the method, and then again using the method. The inter-rater reliability was evaluated for ratings of damage without and with the method. For novice fire investigators rating degree of damage without the aid of the method, ICC(2,1)=.277 with 95% CI (.211, .365), and with the method, ICC(2,1)=.593 with 95% CI (.509, .684). Results indicate that the raters were more reliable in their analysis of the degree of fire damage when using the method, which support the use of standardized processes to decrease the variability in data collection and interpretation.

KEYWORDS: forensic science, fire investigation, fire patterns, inter-rater reliability, gypsum wallboard, fire damage, calcination

Fire investigators use visible observations of fire damage (damage indicators) as their principal means of determining a fire's area of origin (1-6). Some fire investigators have historically used, and in some cases continue to use, these damage indicators as a mechanism by which decisions are made to explain the physical evidence presented without necessarily having a good understanding of the underlying causative fire dynamics. This may have contributed to the promulgation of several myths within the profession (1). Within the past decade, increased scrutiny of the fire investigation profession has been made public through the United States media reporting on several miscarriages of justice due to myths and the lack of standardized procedures used in the past (1,2). Sadly, in many areas of the United States these procedures and prolific use of the myths continue. Over the past decade, momentum has increased within the fire investigation profession to move away from this indexed list of explanations and move towards the use of discrete damage indicators in an attempt to understand the dynamics of how the fire developed and caused the resulting damage (1).

Fire and arson investigation is possibly one of the most complicated facets of the forensic sciences, due to the end result being frequently path independent. Identical or nearly identical damage indicators may result from different fire scenarios leading to a multitude of plausible hypotheses, meaning that multiple paths of the fire could result in similar damage. As such, it would be expected that there are processes and limitations established to assist with the identification of varying degrees of damage remaining after a fire and the link that degree of damage has to the origin of the fire. Currently, however, no process or methodology exists that permits an objective or uniform identification of varying levels of fire damage. Many fire investigation reports, textbooks, and standards inconsistently report degrees of damage, using a wide range of vague modifiers, such as greater, lesser, heavy, light, major, moderate, minor, severe, and large, in an attempt to distinguish between levels of damage that they observe and are trying to convey (1-6). The absence of a formal process combined with the use of vague modifiers when reporting on data that serves as the principal support for an investigator's conclusions results in several major problems. These include unpredictable conclusions, inter-rater and intra-rater reliability issues, and validity issues. Such factors can be seen as shortcomings to admissibility standards of scientific evidence as laid out in Daubert v. Merell Dow Pharmaceuticals (9) in the United States and R v. Mohan (10) in Canada.

To address these concerns, this study involves the development of a structured methodology which can be used to guide identification and characterization of damage indicators. Development of the method is aligned with recommendations from the National Academy of Science review of forensic sciences in the United States, to establish standard terminology and undertake research that address issues of reliability and validity in forensic science (11). Both of these recommendations are fundamental to assist the fire investigation profession. Other forensic science and engineering disciplines (12-13) have benefited significantly from developing clear parameters for identification purposes and standardizing their lexicon, which in turn has permitted a deeper evaluation of their respective forensic science and allowed for integration of advancements in technology.

This paper discusses the development of a degree of fire damage method to characterize gypsum wallboard damage and the evaluation of the inter-rater reliability without and with the application of this method. Gypsum wallboard consists of a core of gypsum (calcium sulfate dihydrate) sandwiched between two thick paper facers (14). Gypsum wallboard has a predictable response to heat and its uniformity in production allow it to be used as a reliable indicator of heat exposure for post-fire analysis (1, 17). There are several effects that may occur to gypsum wallboard when exposed to heat and fire conditions, including color changes, soot deposition, texture changes, charred paper, consumed paper, and clean burn (soot is not observed post-fire and appears to have been consumed). Additionally, when gypsum wallboard is exposed to heat it will undergo a dehydration of chemically bound water, known as calcination, leaving a fragile material in its place (14, 17).

B.1 Methods

Within this paper, four distinct activities are discussed: (a) the development of a degree of fire damage scale, (b) methodology to apply the scale, (c) a study of the method as applied by novices, and (d) statistical analysis to evaluate the method's effectiveness.

B.1.1 Measures

Typically, fire investigators look at the face of all surface linings after a fire and make visible determinations of the varying DOFD. Gypsum wallboard-lined walls and ceilings are one of the most common lining materials utilized in residential and commercial construction. As such, gypsum wallboard will serve as the most beneficial material to begin the development of a method to objectively characterize the DOFD and will be the focus of this study.

As a first step, a DOFD scale was developed as a ranking system to reflect the varying degrees of visible fire damage to gypsum wallboard based on its response to heat exposure and visible damage indicators (VDI). The VDI and their respective varying degrees of damage were compiled from the literature, drawing from the many texts and research studies that detail the impact of heating to gypsum wallboard (14, 17). Next, a scale ranging from 0 to 6 was developed for assigning a DOFD, with 0 indicating no visible damage and 6 indicating complete consumption. Each level within the scale was based on a set of VDIs outlined by the literature review. These VDIs were detailed within each level to characterize the DOFD. The VDIs included color and texture differences. Selected images of the VDI for each level were also provided with the DOFD scale to serve as examples to assist with the analysis (Table B-1 and Figure B-1).

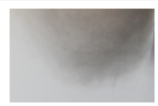
Degree of Fire Damage (DOFD)	**Visible Damage Indicator Description**	**Selected Images of Visible Damage Indicators (corresponding to FIG. 1)**
0	*No visible damage*: these areas are noted by their original surface color (white if unpainted; painted surface color)	
1	*Soot deposited on surface*: these areas are noted by discoloration of the original surface color, but the facing paper is still present	
2	*Discoloration of facing paper and loss of paint*: these are locations of the gypsum wallboard surface that have discolored due to thermal effects, the paper can be brownish, light black, or dark black in color, OR variations in color depending on original paint color	
3	*Paper is beginning to peel, bubble, flake*: the paper has been penetrated and the gypsum wallboard is exposed	
4	*The paper has been consumed*: these areas are typically grey or white in color	
5	*Clean burn*: near complete consumption of paper and soot accompanied by a white/bluish color,	
6	*Complete consumption*: complete loss of integrity and mass of the gypsum wallboard	
N/A	Damage cannot be determined due to suppression or unknown causes	

TABLE B-1 – *Method of Characterizing Degree of Fire Damage along Gypsum Wallboard-lined surfaces.*

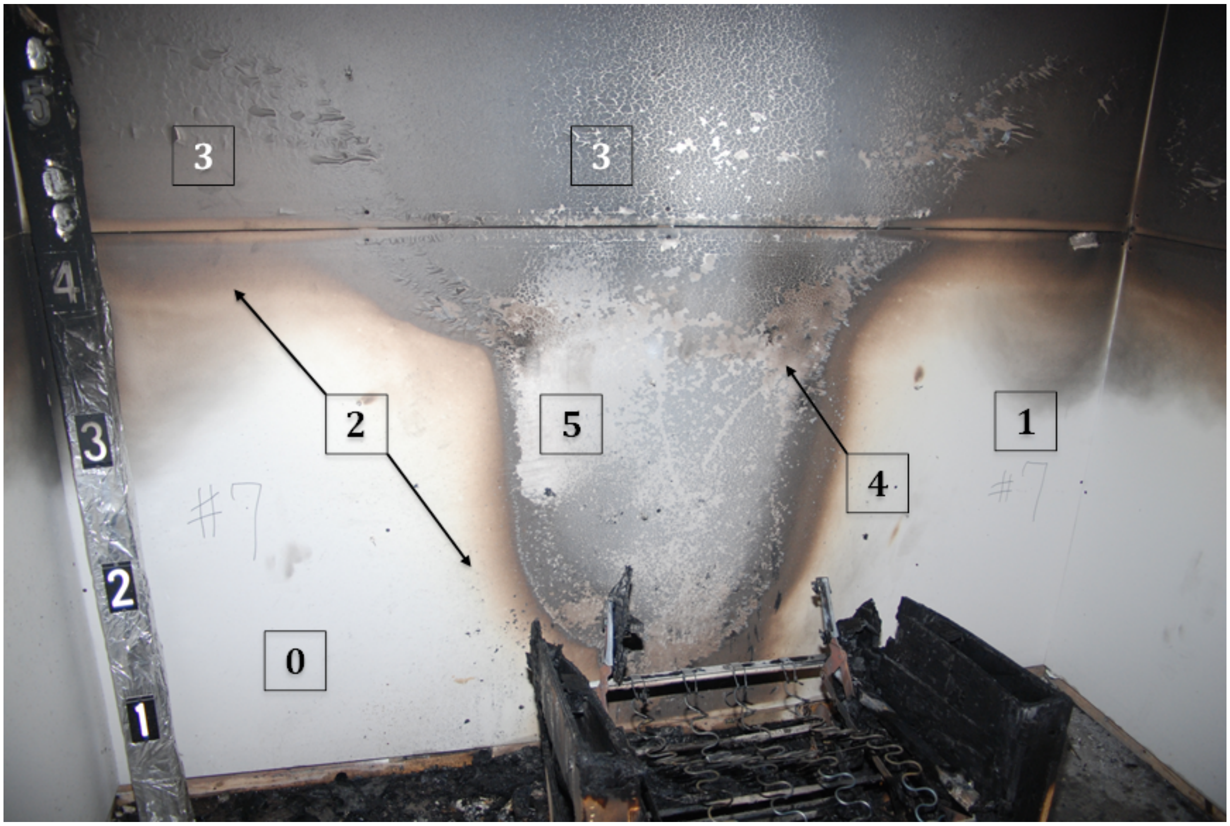


FIG. B-1 – *Photograph from which selected images of visible damage indicators was chosen for use with the DOFD Method.*

A method of characterizing fire damage observed along gypsum wallboard-lined surfaces was developed from combining the ranking scale, example images, description of damage indicators, and instructions on how to apply the method (Table B-1). In order to identify varying DOFD along larger surfaces it is necessary to increase the resolution through the use of a grid system. As such, the user is instructed to establish an appropriate grid size for the surface being evaluated. The user would then evaluate each grid space and characterize the damage within that space. The method further instructed the user to use the example images and damage indicators to characterize the damage observed. Additional instructions were provided to clarify those potential areas of difficulty in ranking. These instructions indicated that the user should be conservative and select the degree of damage with the lower value in the event that the grid space had two varying degrees of damage of equivalent areas (i.e. if a grid space is half soot covered and half no damage, then the user should select no damage for this grid space). Furthermore, instructions were provided that if the grid space includes a seam in the drywall that had been covered with drywall tape and finishing compound, then the participant should determine the most prevalent degree of damage for the gypsum wallboard and ignore the effects of the tape.

B.1.2 Study Design and Sample

To test the reliability of the proposed method, participants (novices) were asked to complete a characterization exercise of a color photograph of a fire damaged gypsum wallboard-lined wall first without the method and then again with the method.

Volunteers were asked to participate as novices applying the method in the study. The participants included 39 undergraduate students in their first course in fire investigation with no formal training or practical experience. Although this was not a random sample, the participants were reasonably representative of typical novices. A single color photograph of a wall damaged from exposure to known fire conditions was chosen for this series of observational tests. An alphanumeric grid was superimposed on the photograph; the columns of the grid were labeled A-K beginning at the left edge of the image, while the rows were labeled 1-6 beginning at the top of the image (Fig. B-1). Each of the 66 individual grid spaces encompassed an area of approximately 0.14 m^2 (0.375m x 0.375m).

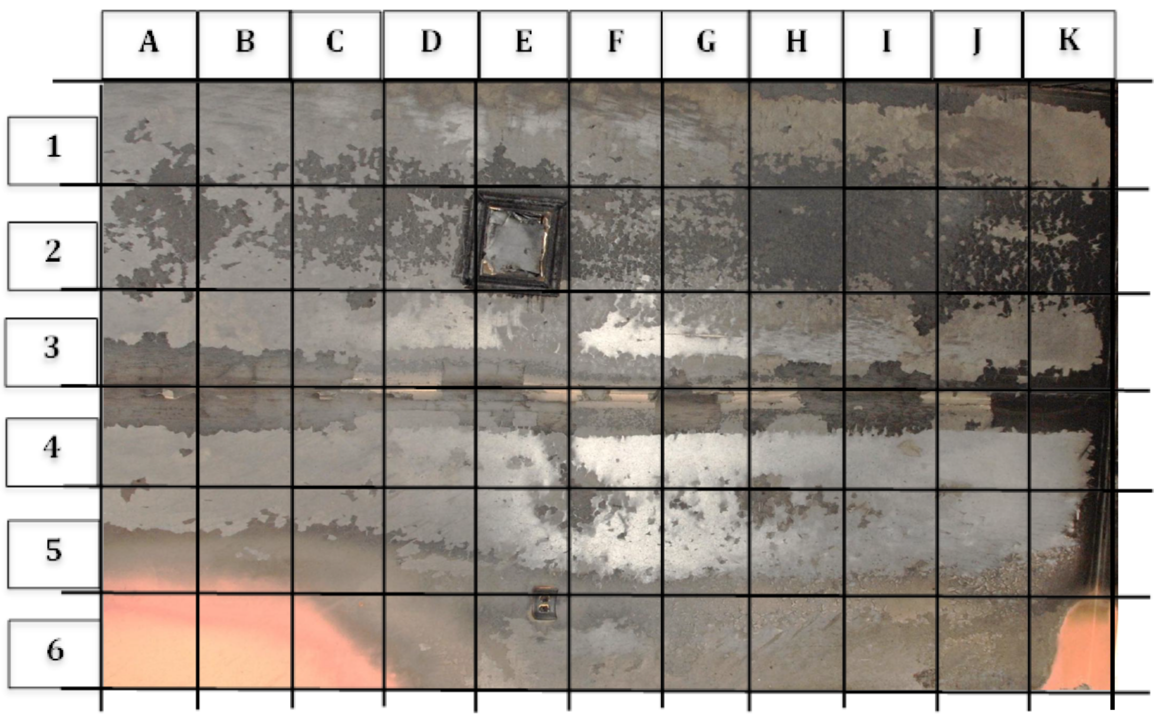


FIG. B-2 – *Photograph of damaged wall with superimposed grid.*

B.1.3 Procedures

Each of the 39 novice participants was supplied with the photograph and 66-grid overlay. First they were asked to rank the most prevalent damage for each grid space based on a scale from 0-6, with 0 indicating no damage and 6 indicating complete consumption. The novice participants performed this first analysis without any methodology and were expected to assign varying degrees of fire damage on their own (as investigators typically do in the field). Next, the participants were provided the same photograph and 66-grid overlay and were asked to provide a rating of 0-6 of the most prevalent degree of damage for each grid space using the degree of fire damage method (Table B-1). They were instructed to carefully read through the method and use it as a reference when identifying damage within a grid space of the photograph.

Ratings from participants were collected electronically using Qualtrics survey software (15). This platform provided the participants with a simple method to record the damage rating for each of the 66 grid spaces by utilizing a dropdown selection menu containing only the values 0-6. The participants were able to return to grid spaces throughout each study and correct errant values. However, once the study was submitted they were no longer able to access their answers. The participants were not permitted to talk to each other as they performed the study. Due to the relatively large number of cells being evaluated, participant fatigue was a concern. An attention verification question was asked in the middle of the survey to ensure that participants were actively engaged in selecting answers and not haphazardly choosing values. Three participants and their results were excluded for failing the attention validation test.

B.1.4 Data Analysis

To assess the reliability of the DOFD method among participants, the intraclass correlation coefficient (ICC) was calculated for the thirty-nine participants. The ICC is a descriptive statistic that quantitatively estimates rater reliability on a scale from 0 to 1 with a higher value indicating stronger agreement between raters. Specifically, ICC(2,1) was selected since each participant rated each of the 66 grid spaces, and absolute agreement was chosen to account for systematic error due to the relatively small sample size (16). Strength of agreement was interpreted according to the following scale to maintain nomenclature consistent with other reliability measures (18):

ICC(2,1)	Strength of Agreement
<0.40	Poor
0.40-0.75	Fair to good
>.75	Excellent

Finally, a paired t-test was conducted to determine if there was a difference in mean overall damage ratings for novices without and with the method. ICCs were calculated using SPSS version 19 for Windows (19); all t-tests were performed using SAS version 9.2 (20). A significance level of $\alpha=.05$ was used throughout.

B.2 Results

For novice fire investigators rating degree of damage without the aid of the DOFD method, ICC(2,1)=.277 with 95% CI (.211, .365). This relatively small ICC value indicates high variability in ratings and poor agreement among participants. For novice ratings making use of the DOFD method, ICC(2,1)=.593 with 95% CI (.509, .684), indicating fair to good agreement among participants.

The mean damage rating for novices without the DOFD method was 3.32 (SD=0.54), while the mean rating with the DOFD method was 3.57 (SD=0.34). It is interesting to note that the mean value of damage significantly increased with the use of the DOFD method ($t=3.52$, $p=.001$), despite the instructions to be conservative in ranking damage.

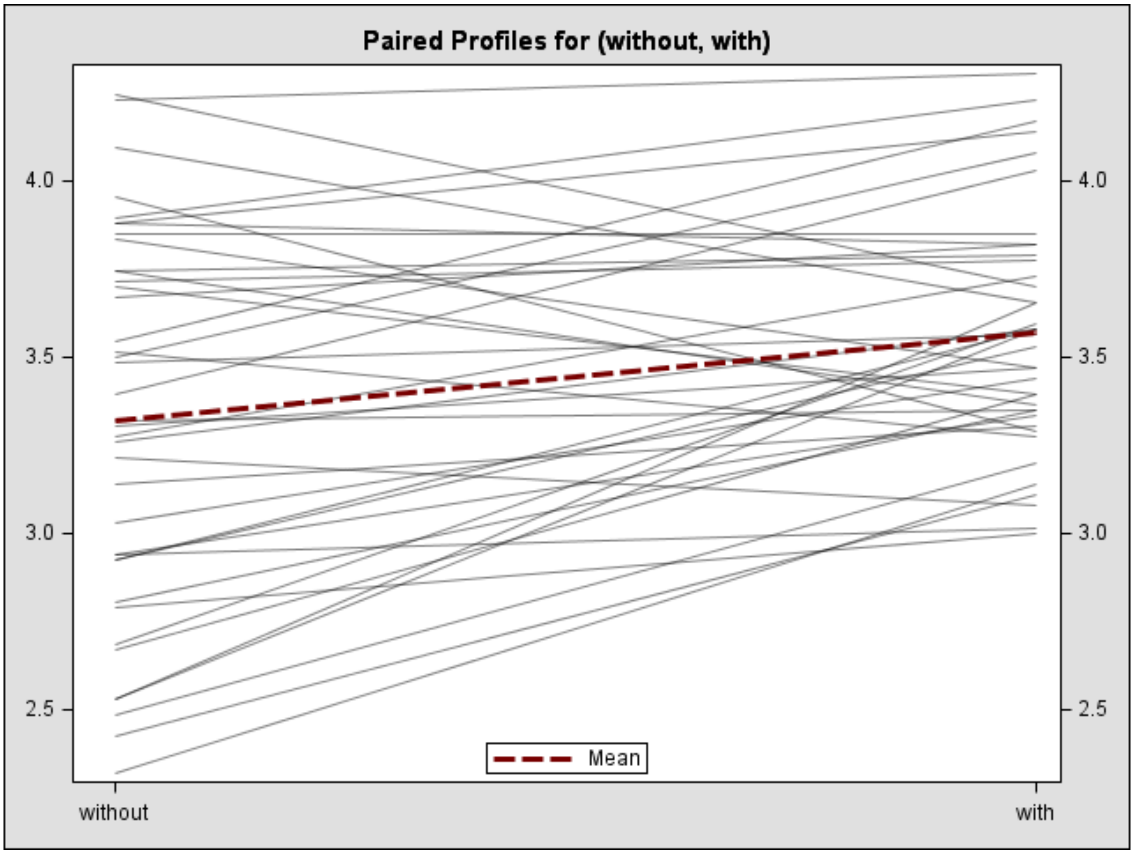


FIG. B-3 – *Change in overall 'novice' rating without method (left) to with DOFD method (right), illustrating decrease in variance*

B.3 Discussion

Since the ICC increases from 0.277 to 0.593 for novices without and with the DOFD method, respectively, the agreement among raters is increasing and the variability in their ratings is decreasing. This decrease in variability of the novice's ratings with the method illustrates the reliability of the DOFD method.

The simple DOFD method presented in this study has been shown to decrease the variability among novices and increases the reliability in ranking fire damage to gypsum wallboard.

Even though this study has shown a reduction in variability in the degree of fire damage among novices, it is interesting to determine if these results are similar to that of expert practitioners. Due to time constraints, a limited convenience sample of four expert fire investigators was used to rate the degree of fire damage using the method. The expert ratings had almost no variability (mean overall damage rating for the experts was 3.62; SD=0.04). It is interesting to note that novices had an overall damage rating of 3.32 without the method, which increased to 3.57 with the method. This trend, despite the limited expert sample, may indicate that novices when using the method are rating damage similarly to the expert practitioners. Further testing will need to be conducted with expert practitioners to further evaluate this trend.

The DOFD method will need to be further tested against a variety of fire damaged gypsum wallboard-lined walls with various paint schemes to further evaluate its reliability and consistency.

B.4 Conclusion

A new method is presented for characterizing the degree of fire damage to gypsum wallboard-lined surfaces. Thirty-nine independent "novice" raters performed a visual analysis of damage to a wall surface, completing 66 ratings first without the degree of fire damage method and second, repeated rating with the DOFD method. The interrater reliability was evaluated for ratings of damage without and with the method. The results indicate that the novice raters were more reliable in their analysis of the degree of fire damage to gypsum wallboard when using the DOFD method. These results support the use of standardized processes to decrease the variability in data collection and interpretation.

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APPENDIX C – POD Example: Proof of Concept

The compartment for this example was constructed of 2x4 wood members with the following dimensions: 2.44m wide x 2.49m tall x 2.44m deep. The walls and ceiling were lined with 0.013m thick gypsum wallboard (Figure C-1). An opening was placed in the south wall that was varied throughout the test series. The ventilation opening for the test encompassed the full width of the wall.

An overstuffed polyurethane foam recliner was utilized as the only fuel within the compartment. The point of origin for the fire was near the center of the recliner at the point where the backrest cushion and seat cushion meet. The fire was extinguished when approximately 30-31 lbs of mass was lost (Table C-1).

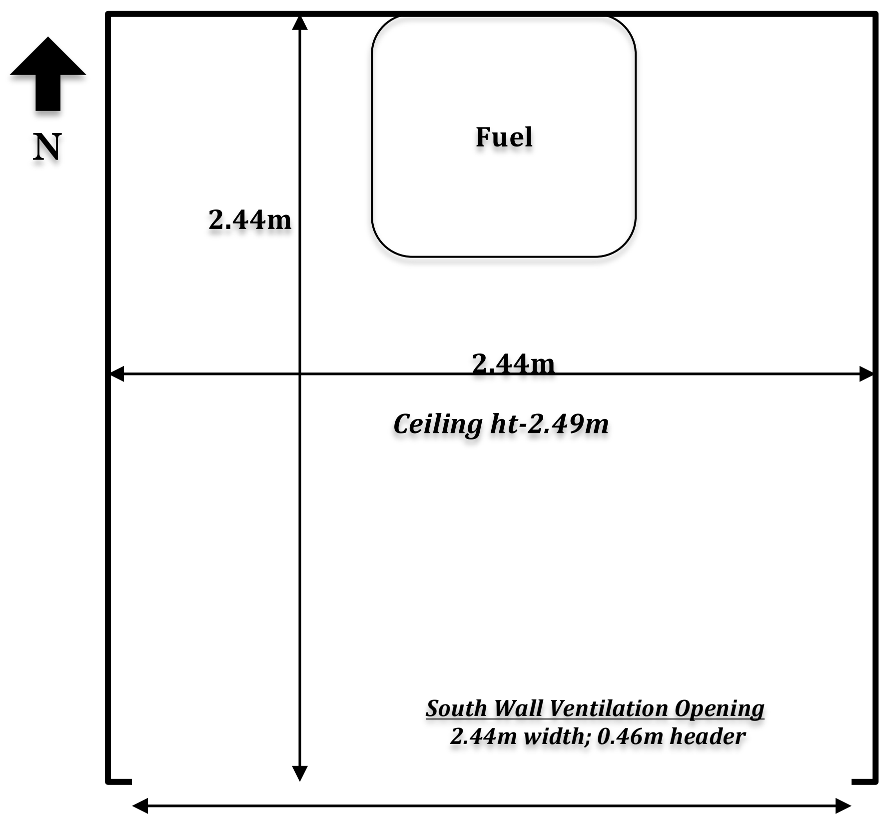

Figure C-1: Compartment layout and dimensions

Table C-1: Test Data

BURN	STARTING MASS - lb (kg)	ENDING MASS – lb (kg)	MASS LOSS – lb (kg)	TIME - Min (sec)	HEADER HEIGHT INCHES
1	86.75 (39.32)	56.31 (25.54)	30.44 (13.78)	8:59:44 (539)	18”

Figure C-2: Photographs of fire damaged walls (left) and ceiling (right)

Step 1: Identifying the value in further analysis of a surface or compartment

The three walls and ceiling within this compartment were damaged. Therefore, all of the surfaces will be evaluated through the remainder of the process (Figure C-2). The content item surfaces will not be evaluated through this example.

Step 2: Assessment of the varying degrees of fire damage (DOFD) along a single surface

Question 1: Is there varying degrees of thermal damage along the surface? All gypsum wallboard surfaces (3 walls, 1 ceiling) were analyzed for the varying degree of fire damage using the visible DOFD scale method (Tables C-2, C-3). The degree of fire damage methodology for gypsum wallboard was utilized to assign a numerical value for varying degrees of fire damage along the surface based on the visible damage indicators noted. A 1 ft x 1ft grid was established over all gypsum wallboard surfaces. Each grid space was provided a DOFD value, with a scale ranging from 0 to 6 based on the visible damage indicator noted. Note that the digital image analysis and depth of calcination methods were not employed within this example.

Table C-2: Test 4 DOFD Assessment of the Walls (1' x 1' grid spaces)

West Wall								*North Wall*								*East Wall*							
2	2	2	2	3	3	3	3	4	3	3	3	3	3	3	4	4	3	3	3	2	2	2	2
2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2	3	4	3	3	2	2	2	2	2	2	2	2	2	2
1	1	1	1	1	1	1	1	1	0	4	5	4	4	0	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	5	4	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	5	4	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	5	4	0	0	0	0	0	0	0	0	0	0	0

Table C-3: Test 4 DOFD Assessment of the Ceiling (1' x 1' grid spaces)

	North								
W e s t	4	2	3	3	3	2	2	2	*E* *a* *s* *t*
	3	2	2	3	3	2	2	2	
	3	2	2	2	2	2	2	2	
	4	2	3	3	3	2	2	2	
	2	2	2	2	2	2	2	2	
	2	2	2	2	2	2	2	2	
	2	2	2	2	2	2	2	2	
	2	2	2	2	2	2	2	2	
	South								

Step 3: Identification of trends of damage along surfaces within the compartment.

The purpose of this step is to objectively identify the areas of greater damage and the trends with those areas of damage within the compartment. Ultimately each surface that exhibits a cluster of thermal damage will be ascribed as a single pattern or grouped with other damage that has been shown to extend along other surfaces as a pattern, thus providing the analyst a discrete number of patterns that must be analyzed through step four of the process. If a trend is identified, either along a single surface or extends across multiple surfaces, it should be noted as a fire pattern. If no trend exists, then the surface will need to be evaluated through step 4. The following 7 steps have been proposed to find these areas and trends:

1. Perform gradient calculations for the DOFD matrices for each surface.
2. Plot the gradient changes (Figure C-3).
3. Use a quiver plot to illustrate the gradient changes as vectors overlaid on the contour plot (Figure C-4). The vectors illustrate the direction from lesser to greater damage (smaller to larger numbers) and the length of the arrow depicts the magnitude associated with that change.
4. To identify areas of greater damage and the trends associated with these areas, a threshold for the gradients was selected as greater than or equal to 1.0 (Figures C-5).
5. The area(s) of damage will be identified through this progressive gradient thresholding process (Figures C-5).
6. Each surface should be evaluated independently for areas of greater damage and their respective trends. Next, a comparison of all surfaces within the compartment will be performed.
7. Each area of damage identified will be catalogued as a fire pattern and assessed through step four in the process (Figure C-6).

Contour plots were created for each surface as a means to better visualize the varying DOFD along each surface (Figure C-6) as well as to assist with the next step within the process.

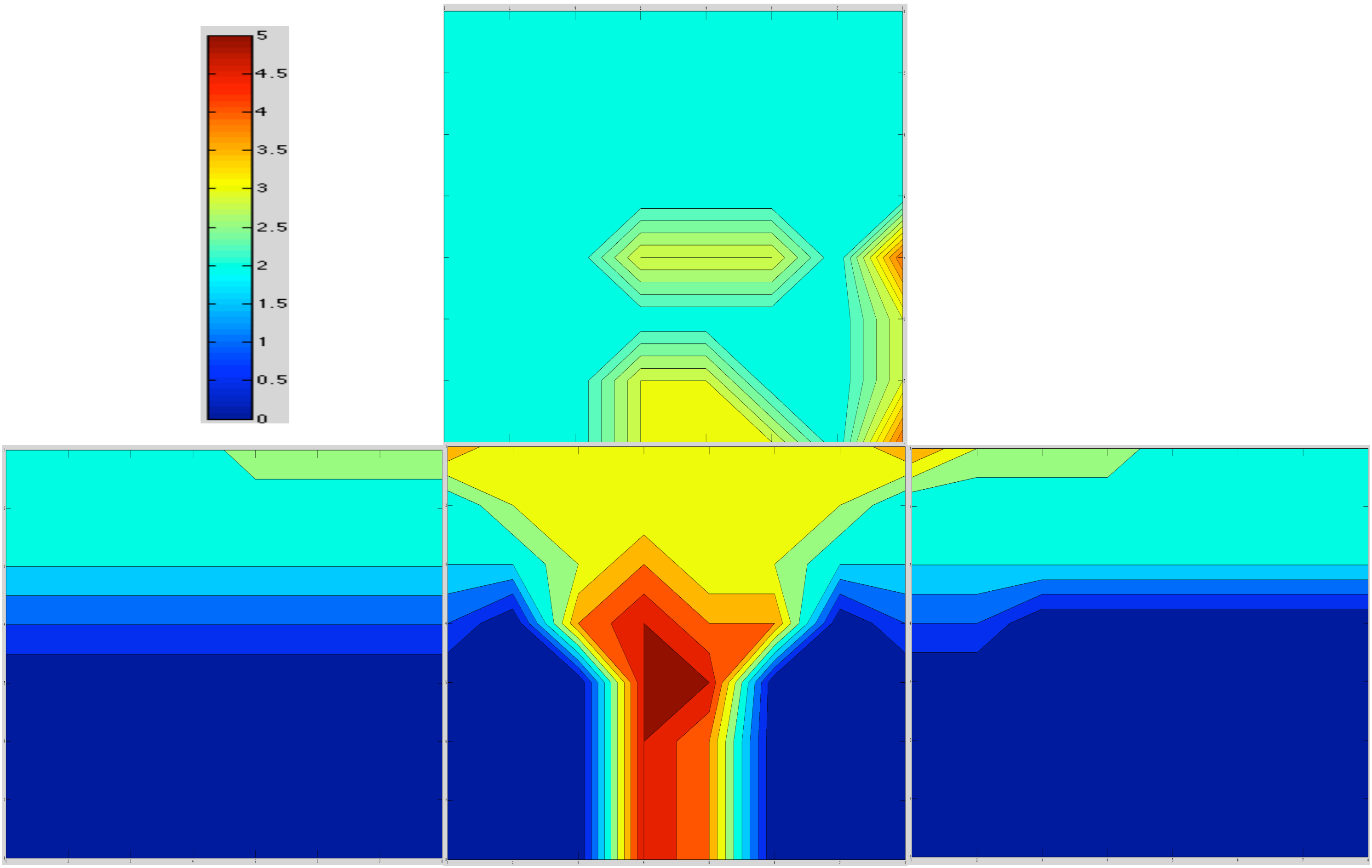

Figure C-3: Contour plots of each wall and ceiling (exploded view w/ west, north, and east walls arranged below the ceiling)

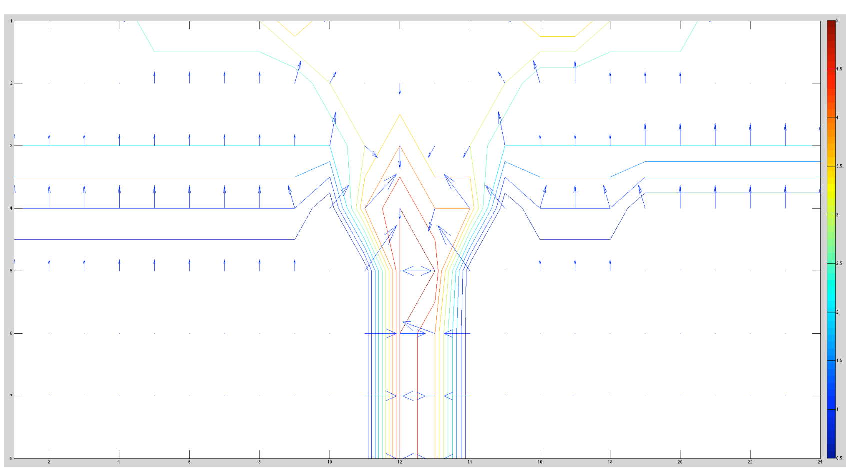

Figure C-4: Quiver Plot Illustrating the Gradient Field Vectors of the DOFD for all three walls

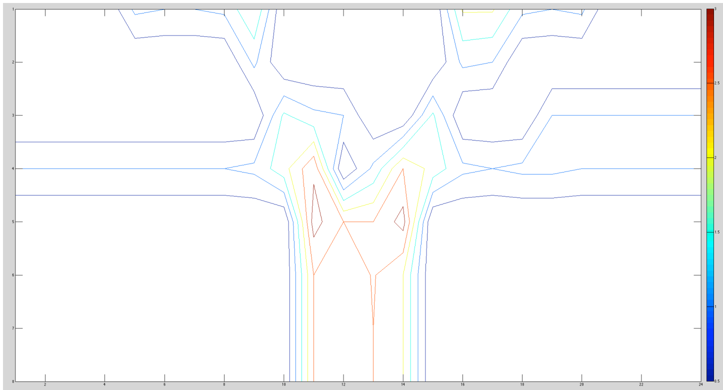

Figure C-5: Plot of the Gradients that are greater than or equal to 1.0

Identification of Fire Patterns

The three wall surfaces are evaluated independently starting with the greatest gradient change. Each cluster of damage will be identified as a fire pattern.

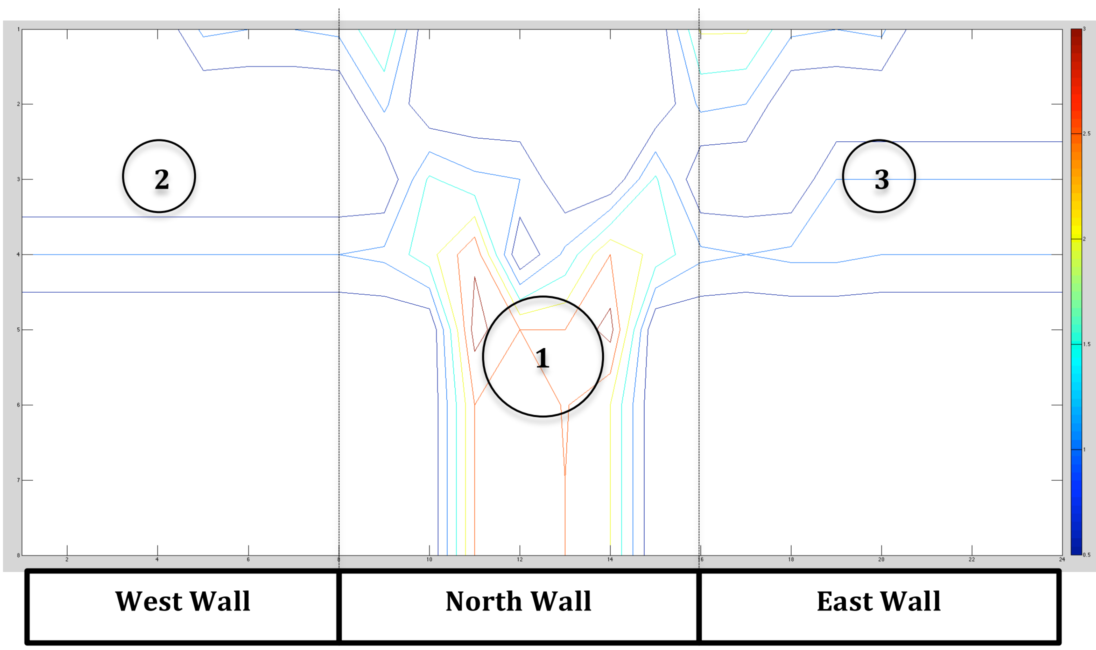

Figure C-6: Identification of the Fire Patterns

There are three areas of damage identified when gradients of greater than 1.0 are evaluated.

Step 4 – Fire Pattern Generation - Prototype of Identifying Relationships of Fire Pattern Generation with Bayesian Networks and Probabilistic Inference

Each fire pattern will be evaluated through the fire pattern generation step.

4.1 Burning Regime Determination

First, the burning regime needs to be analyzed. The prediction of flashover was based on the methods of Thomas, Babrauskas, and MQH to estimate the minimum HRR required to flashover the compartment resulted in a range between 1400-5000kW. As the Polyurethane chair is estimated to have a significantly less peak HRR, flashover is not predicted. The damage cues were also evaluated. Damage was not identified low throughout the compartment, therefore, this damage cue will be identified as ‘false’. As there was only one combustible item within the compartment and significant loss of mass was observed to this item, then this damage cue will be identified as ‘true’. The BN with the evidence introduced is shown in figure C-7. The burning regime is determined to be fuel-controlled.

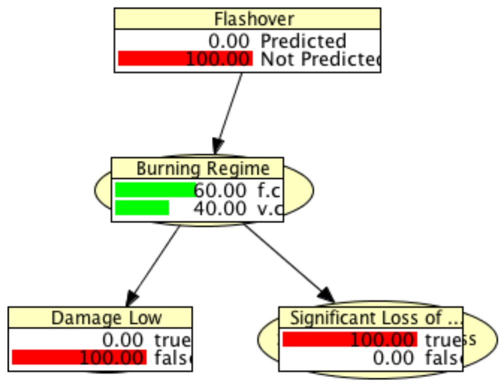

Figure C-7: Burning Regime BN with Evidence Introduced

Since the BN reflects that this fire was most likely a fuel-controlled burning regime, only the plume generated damage and upper layer generated BNs will be evaluated.

4.2 Fire Pattern 1

Fire pattern 1 (Figure C-6) was evaluated first through plume generated BN. Each damage cue will be evaluated. Table C-4 lists the damage cues and the findings related to these cues. All of the evidence was entered into the BN and the likelihood ratios were calculated (Figure C-8).

Table C-4: Damage Cues related to PG for Fire Pattern #1

Damage Cue	Meaning	True / False
1	Loss of mass to fuel is consistent with damage to affected surface	True
2	Increased magnitude of damage near fuel item	True
3	Elevation of the line of demarcation is consistent with the height of the fuel item	True
4	Width of the base of damage is approximately the width of the fuel item and no greater than 2 times the width of the fuel	True
5	Lines of demarcation are angled emanating from the fuel item	True

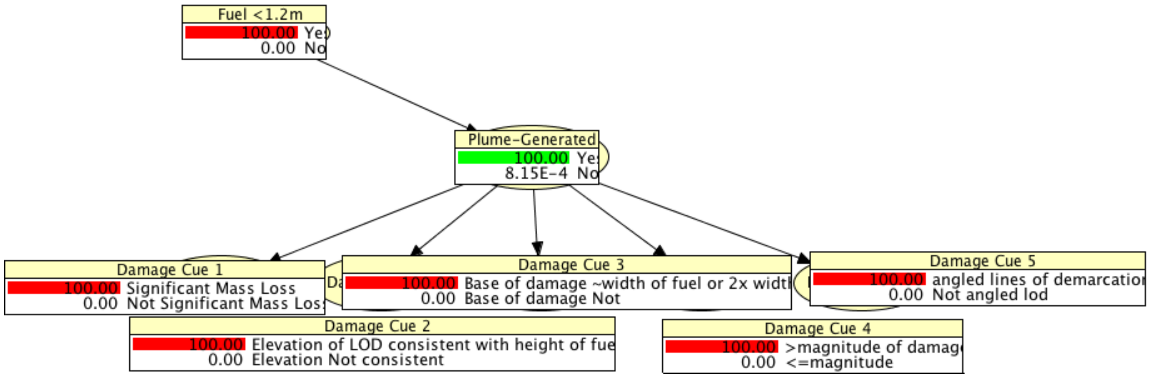

Figure C-8: PG BN for FP#1

Table C-5: Damage Cues related to ULG for Fire Pattern 1

Damage Cue	Meaning	True / False
1	Damage High in Elevation	False
2	Uniform magnitude of damage	False
3	Increasing line of demarcation out of ventilation opening	False

Next, fire pattern 1 was processed through the upper layer generated BN. Each damage cue was evaluated and defined in Table C-5. All evidence was entered into the ULG BN and the likelihood ratios calculated (Figure C-9).

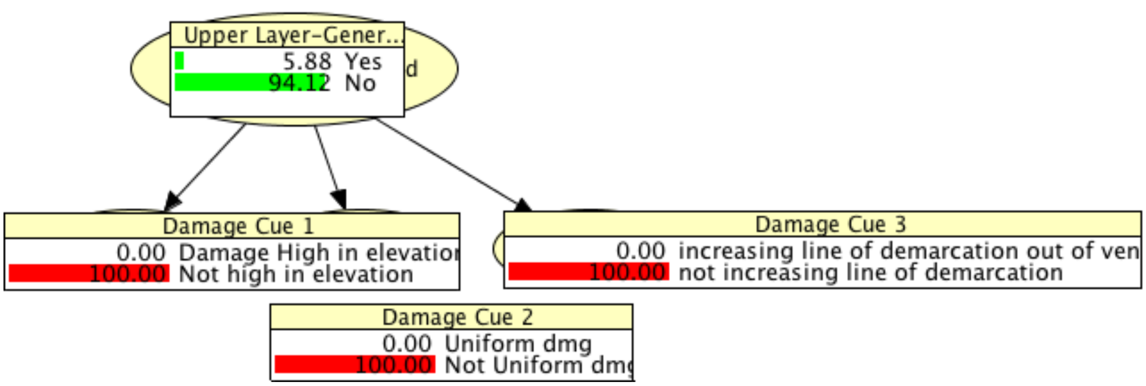

Figure C-9: ULG BN for FP#1

Fire pattern 1 is strongly consistent with being a plume-generated damage.

4.3 Fire Pattern 2

Fire pattern 2 (Figure C-6) was evaluated through the plume generated BN. Each damage cue will be evaluated. Table C-6 lists the damage cues and the findings related to these cues. All of the evidence was entered into the BN and the likelihood ratios were calculated (Figure C-10).

Table C-6: Damage Cues related to PG for Fire Pattern #2

Damage Cue	Meaning	True / False
1	Loss of mass to fuel is consistent with damage to affected surface	True
2	Increased magnitude of damage near fuel item	False
3	Elevation of the line of demarcation is consistent with the height of the fuel item	False
4	Width of the base of damage is approximately the width of the fuel item and no greater than 2 times the width of the fuel	False
5	Lines of demarcation are angled emanating from the fuel item	False

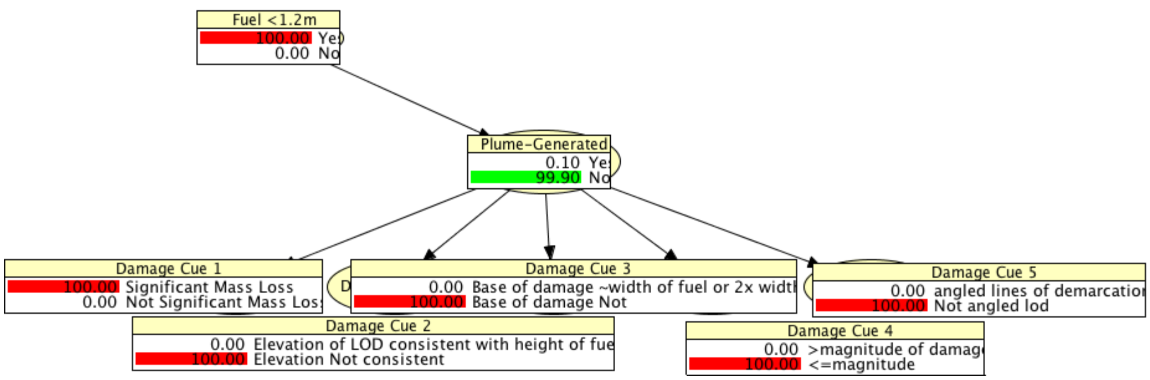

Figure C-10: PG BN for FP#2

Next, fire pattern 2 was processed through the upper layer generated BN. Each damage cue was evaluated and defined in Table C-7. All evidence was entered into the ULG BN and the likelihood ratios calculated (Figure C-11).

Table C-7: Damage cues related to ULG for fire pattern 2

Damage Cue	Meaning	True / False
1	Damage High in Elevation	True
2	Uniform magnitude of damage	True
3	Increasing line of demarcation out of ventilation opening	True

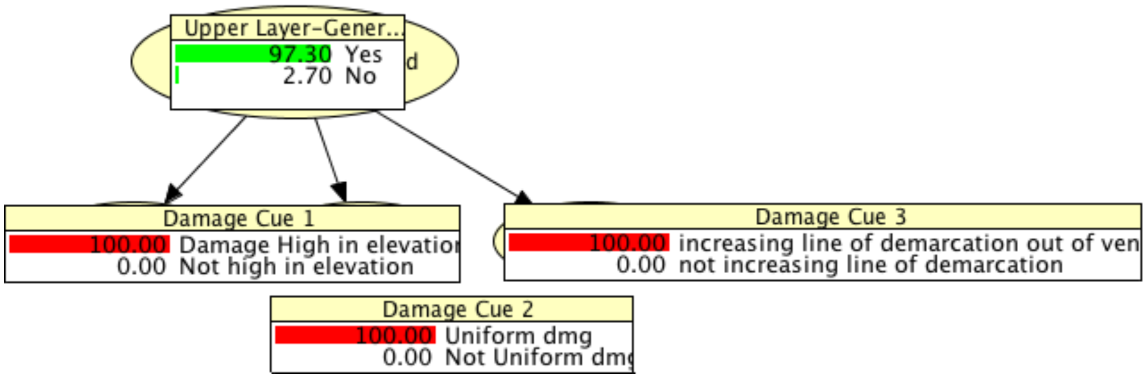

Figure C-11: ULG BN for FP#2

Fire pattern 2 is strongly consistent with being an upper layer-generated damage.

4.4 Fire Pattern 3

Fire pattern 3 (Figure C-6) was evaluated through the plume generated BN. Each damage cue will be evaluated. Table C-8 lists the damage cues and the findings related to these cues. All of the evidence was entered into the BN and the likelihood ratios were calculated (Figure C-12).

Table C-8: Damage Cues related to PG for Fire Pattern #3

Damage Cue	Meaning	True / False
1	Loss of mass to fuel is consistent with damage to affected surface	True
2	Increased magnitude of damage near fuel item	False
3	Elevation of the line of demarcation is consistent with the height of the fuel item	False
4	Width of the base of damage is approximately the width of the fuel item and no greater than 2 times the width of the fuel	False
5	Lines of demarcation are angled emanating from the fuel item	False

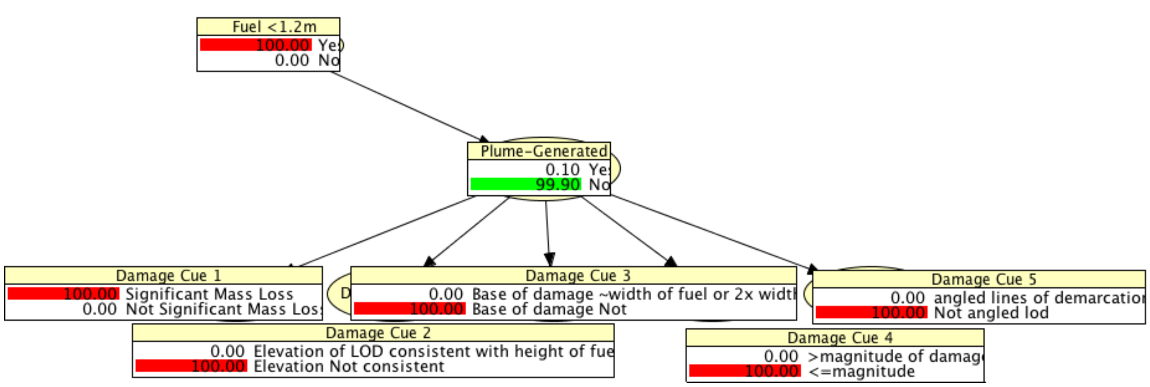

Figure C-12: PG BN for FP#3

Next, fire pattern 3 was processed through the upper layer generated BN. Each damage cue was evaluated and defined in Table C-9. All evidence was entered into the ULG BN and the likelihood ratios calculated (Figure C-13).

Table C-9: Damage cues related to ULG for fire pattern 3

Damage Cue	Meaning	True / False
1	Damage High in Elevation	True
2	Uniform magnitude of damage	True
3	Increasing line of demarcation out of ventilation opening	True

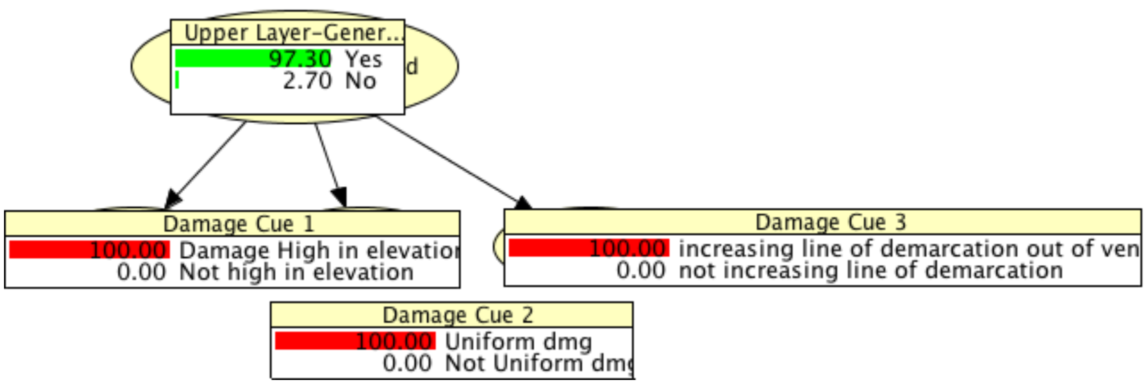

Figure C-13: ULG BN for FP#2

Fire pattern 3 is strongly consistent with being an upper layer-generated damage.

Step 5 – Development of the Hypothetical Area(s) of Origin

Fire pattern 1 is the only fire pattern consistent with a plume. Therefore, it is selected as the area of origin.

References

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Hicks W, Gorbett G, Hopkins M, Kennedy P, Hopkins R, Thurman T (2008) Full-Scale Single Fuel Package Fire Pattern Study. Paper presented at the International Symposium on Fire Investigations, Investigations Institute, Florida (USA)

APPENDIX D – Numerical Experiments

The compartment simulated was a 3.66m x 3.66m x 2.44m in height (12ft x 12ft x 8ft), with a single door vent measuring 0.91m x 2.0m (3ft x 6ft-7in). The walls, ceiling, and contents were simulated to be room temperature constant-properties of gypsum wallboard. These generic material properties were used for all simulations and were not intended to truly model the changing properties of gypsum wallboard. A total of 807 devices were placed within the simulation (Figure D-1). Three thermocouple trees were placed within the compartment including one located in the doorway, one in the center of the room, and one adjacent from the doorway opening. Three heat flux gauges were located on the floor in the center of the room, center of the doorway, and adjacent from the doorway. Finally, a total of 803 devices were located along the walls, ceiling, and content surfaces at 0.3m (1 ft) increments to record the time integral net heat flux (MJ/m^2). In addition to the devices, a time integral gauge heat flux boundary file was simulated. A moderate mesh size was used for all simulations. The mesh resolution was determined using the non-dimensional expression D*/δx, where D* is a characteristic fire diameter

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5}$$

and δx is the nominal size of a mesh cell (McGrattan, et. al, 2014). The 4000 kW fire would provide a D^* of 1.67. Therefore, a fine mesh size was used (&MESH IJK=80, 80, 48), providing a D*/dx of 20.1.

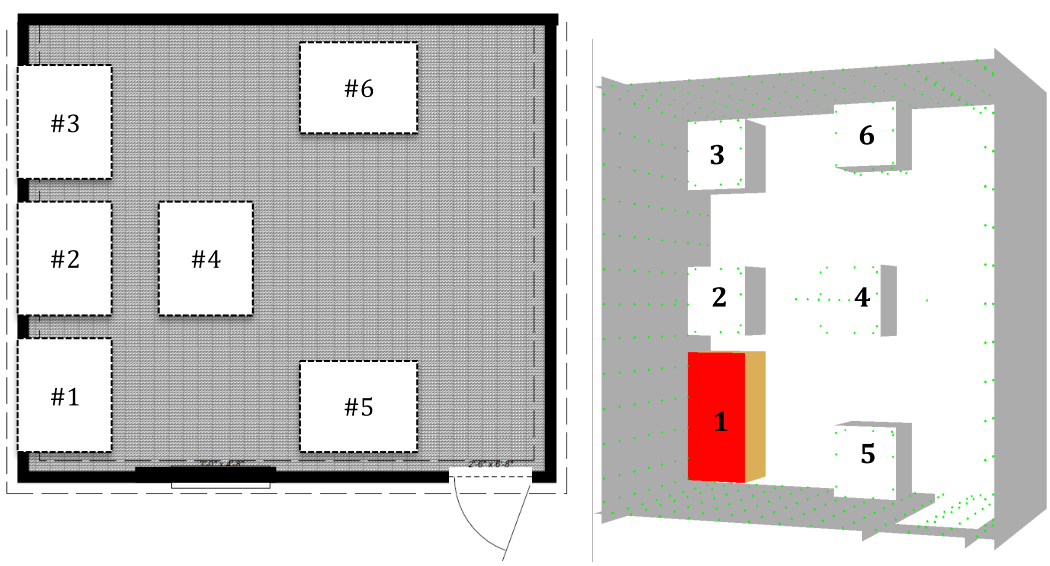


Figure D-1: Compartment Layout (a) floor plan w/fire positions identified (b) Smokeview simulation w/fire positions identified

The fire position (origin) was varied throughout the simulations between against the wall (fire positions 1-3, 5-6) and near wall fires (fire position 4) (Figure 6). Five simulations were completed for each fire position for a total of 30 simulations. The fire growth rate, heat release rate ($\dot{Q}$) over the duration of the fire, for all simulations initially followed a fast t² fire growth curve. The peak heat release rate was varied for each fire position with five peak heat release rates simulated, including 750kW, 1000kW, 1500kW, 3000kW, and a 4000kW (Figure D-2). The two lower peak heat release rates were to establish location and magnitude of heat fluxes throughout the compartment under fuel-controlled conditions, while the last three heat release rates were to evaluate the transition to ventilation-controlled conditions and the associated heat fluxes. The maximum heat release rate supported by the door vent is 3,860kW as calculated by using the following equation:

$$\dot{Q}_{max} = 1500 A_v \sqrt{h_v}$$

Where:

$\dot{Q}_{max}$	=Maximum heat release rate given the ventilation opening
A_v	=Area of the ventilation opening (w_v*h_v)
$\sqrt{h_v}$	= Height of the ventilation opening

A simulated propane gas burner was used for all simulations. Each simulation was run for 1000 seconds.

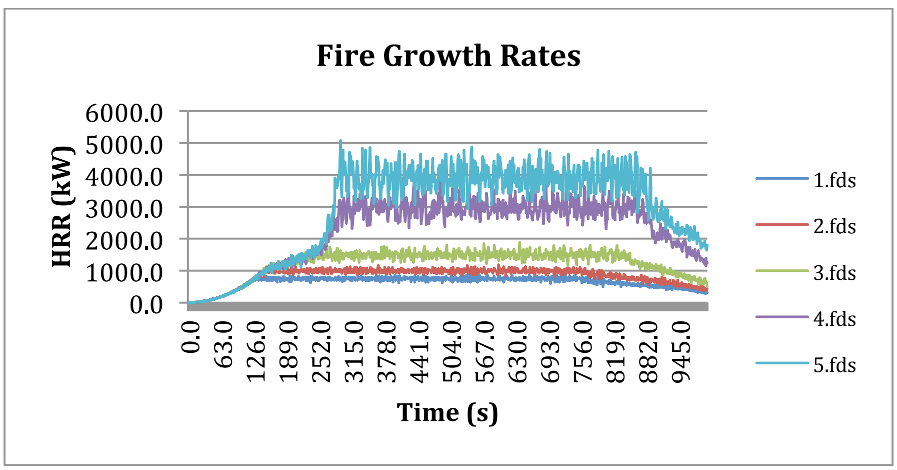


Figure D-2: Fire Growth Rates Simulated for Each Fire Position

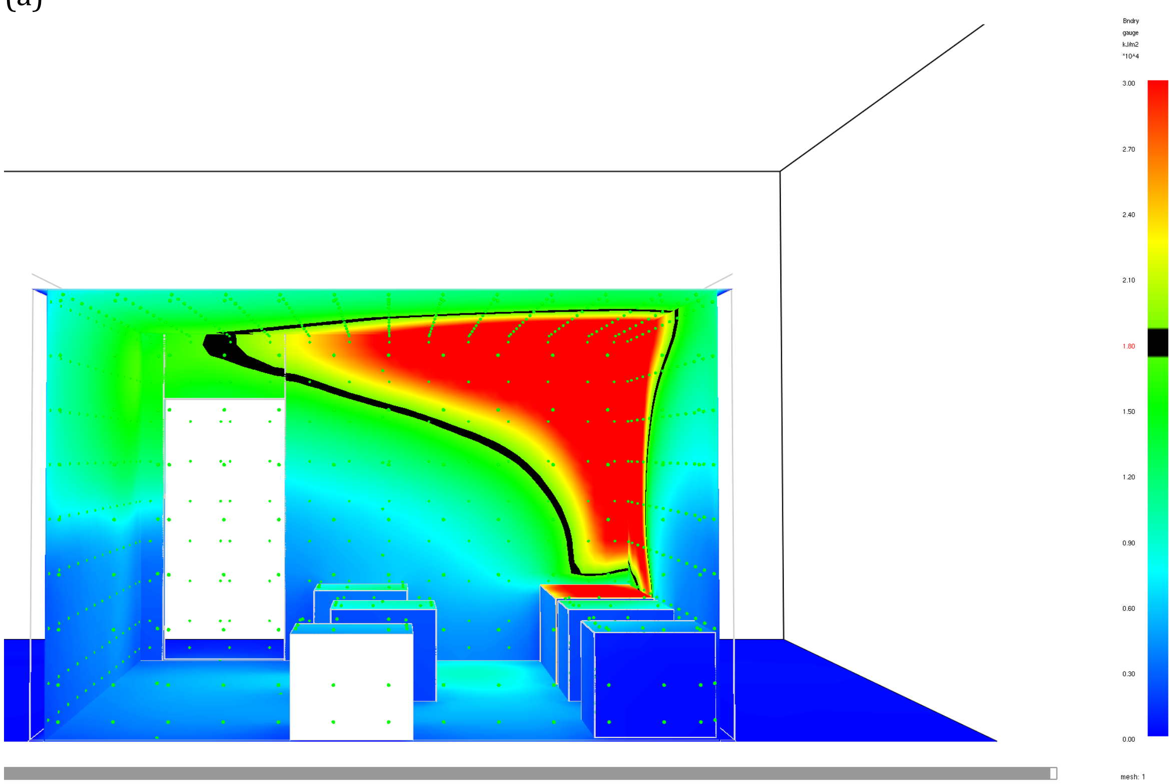
Since the simulations were being evaluated as to the prediction of the location and magnitude of visible and possibly measurable damage, a threshold would need to be established as to what constitutes damage within the FDS simulations. Mealy, Wolfe, and Gottuk (2013) discussed findings related to the visual identification of surface damage progression to gypsum wallboard based on imposed total heat fluxes. They further confirmed the Mann and Putaansuu's progressive visible damage to the surface of the gypsum wallboard. As such, this total imposed heat flux for the duration of the simulation was captured and evaluated. The time integral gauge heat flux boundary file was evaluated using Smokeview. The grid of devices for each wall and ceiling surfaces were evaluated as contour plots. A MATLAB code was constructed to automate the development of the time integral net heat flux contour plots for every 60 seconds, 17 time steps for each simulation (Appendix E-FDS and MATLAB Code).

D.1 Simulation Results

The metric used to evaluate if differences could be discerned to the location and magnitude of damage for these simulations was whether or not the greater time integral net heat flux values deviated from the true origin. The values of 18MJ/m^2 and 39 MJ/m^2 were used as benchmarks to evaluate the progressive contrasts in damage (Mealy et al. 2013).

The location and magnitude of the time integral net heat flux for the 750-1500kw fires for all six fire positions did not deviate from the actual origin. The greatest areas of heat flux could still be found at the area of origin with decreasing heat flux away from the true origin. The disparity between the true origin and other areas of heat flux was often times considerable, indicating that there would be significant differences in the location and magnitude of damage that may result in clear lines of demarcation (Figures D-3 through D-4). Thus, the true origin should be relatively easy to determine regardless of duration of exposure.

(a)



(b)

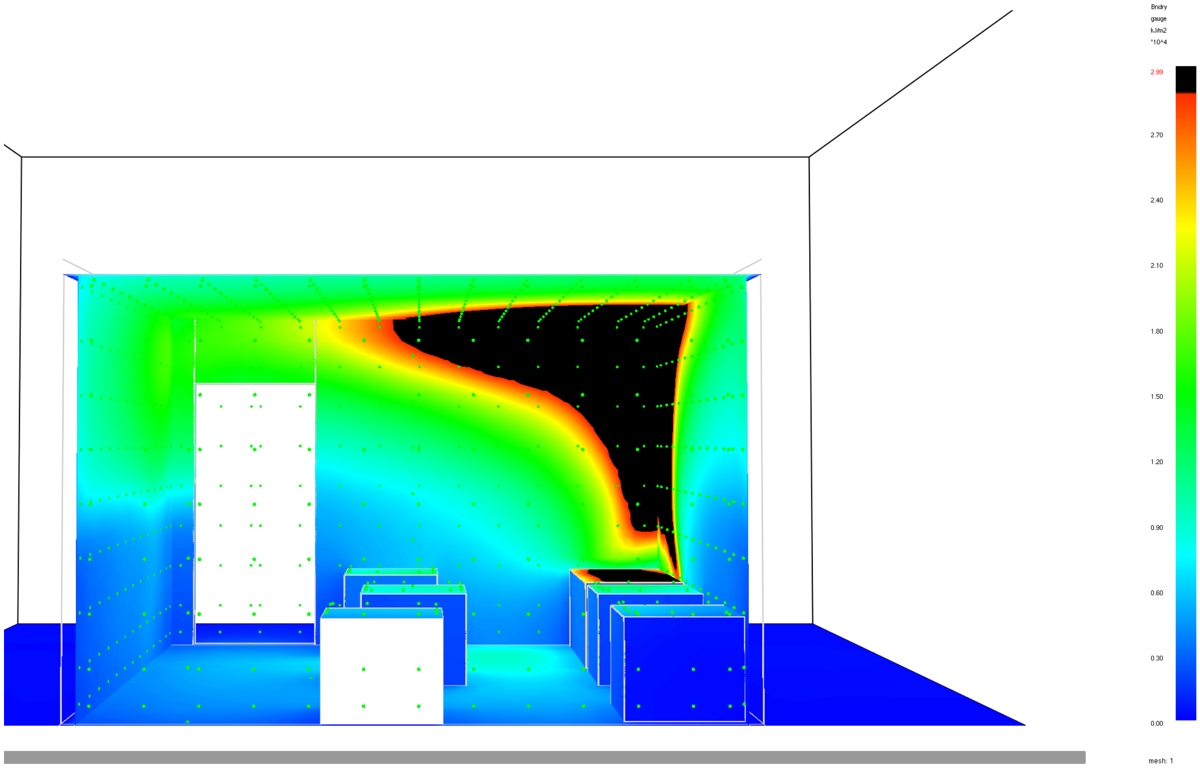
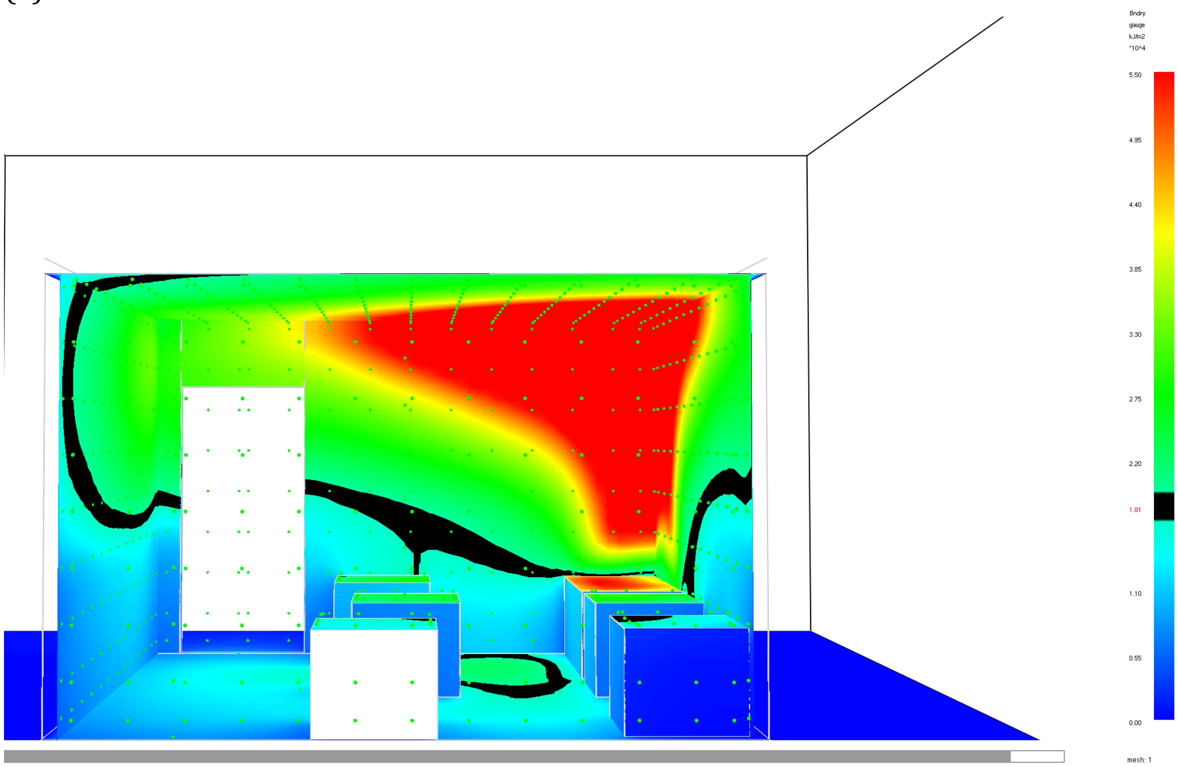


Figure D-3: Fire Position 1 750kW-Smokeview Boundary File Time Integral Gauge Heat Flux (a) 18MJ/m² outlined at 995s (b) maximum heat flux of 29.9 MJ/m² at 1000s black area

(a)



(b)

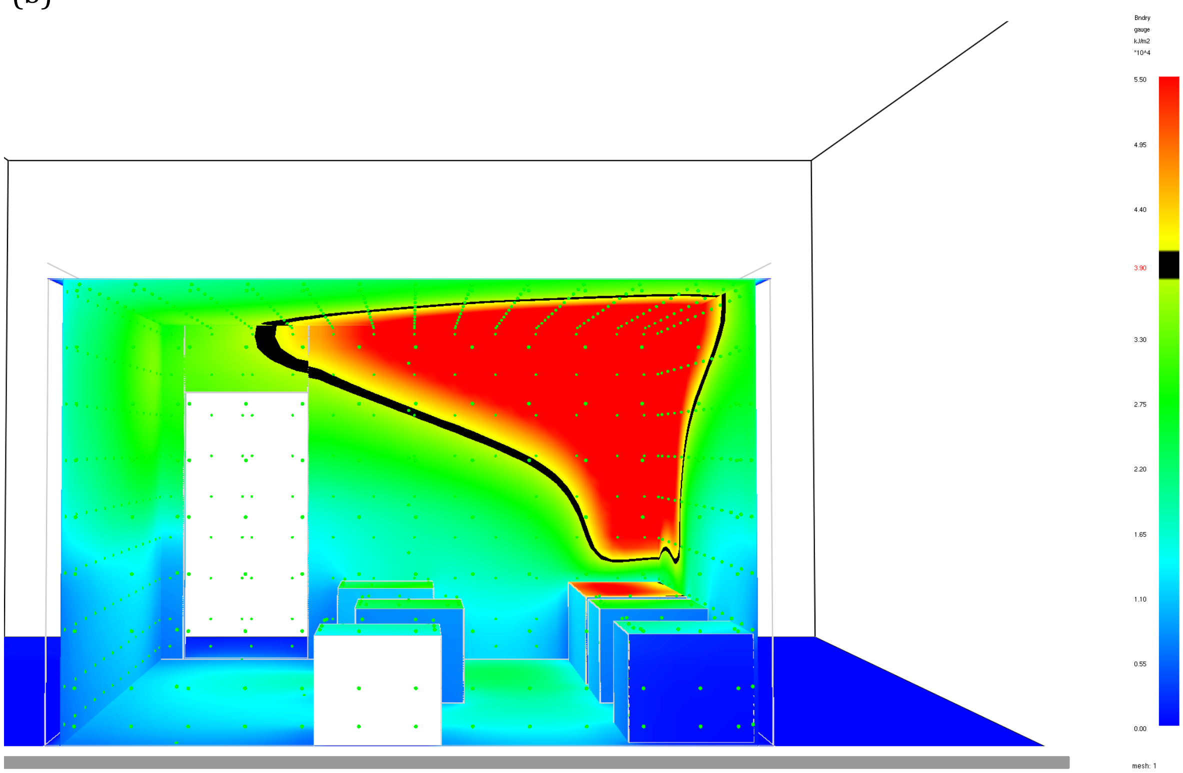
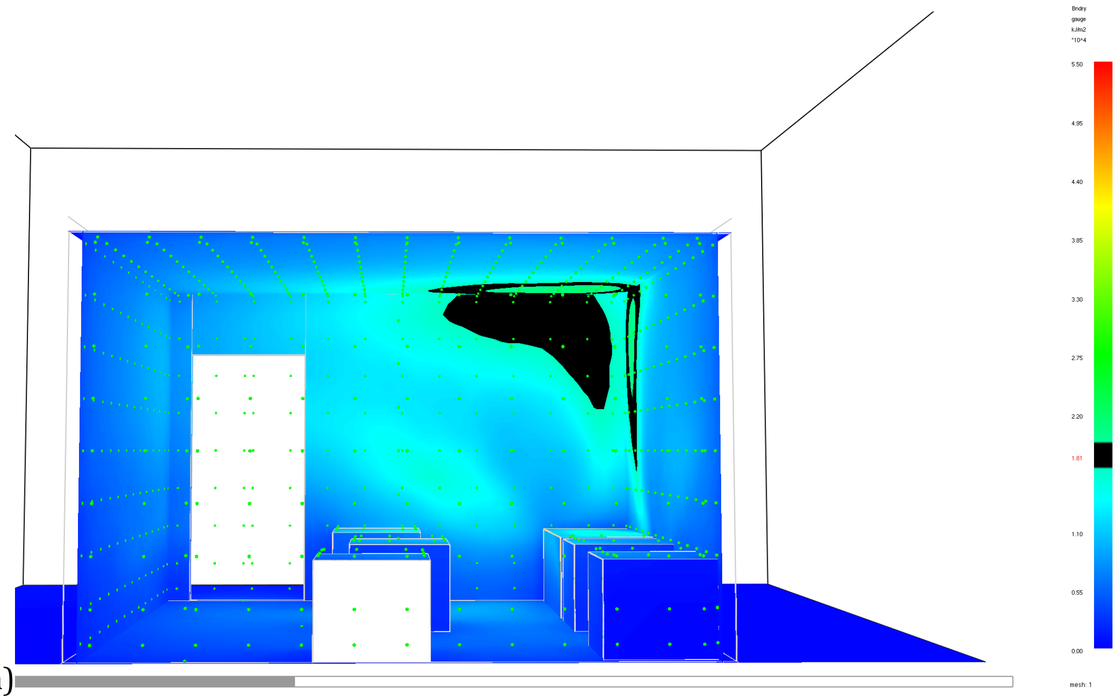
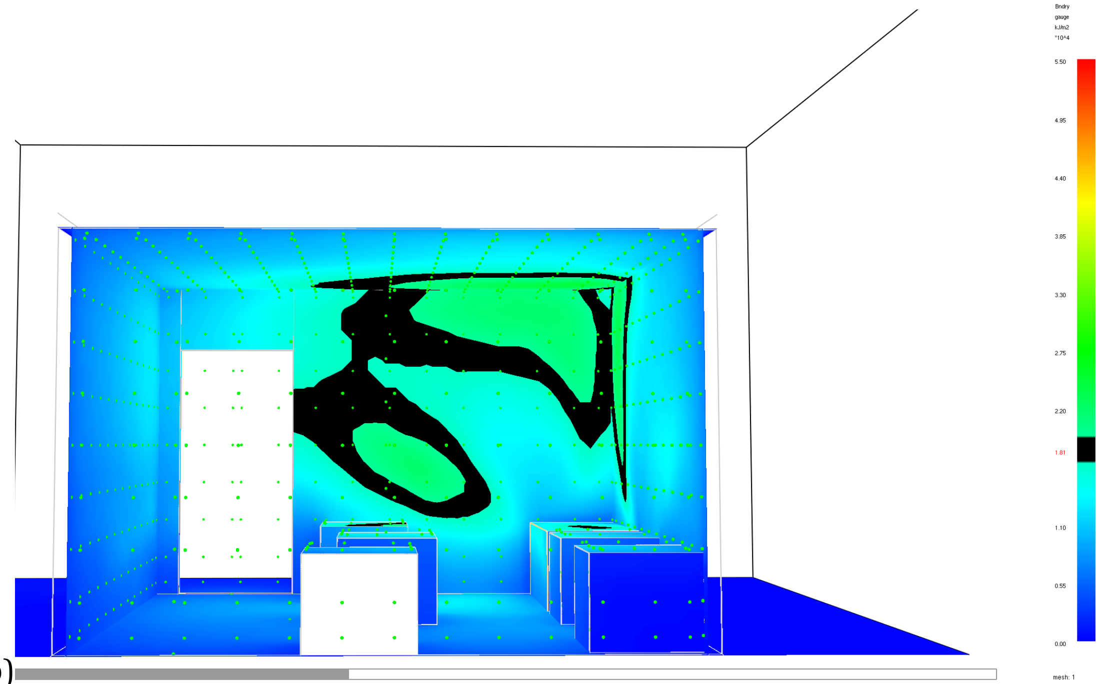


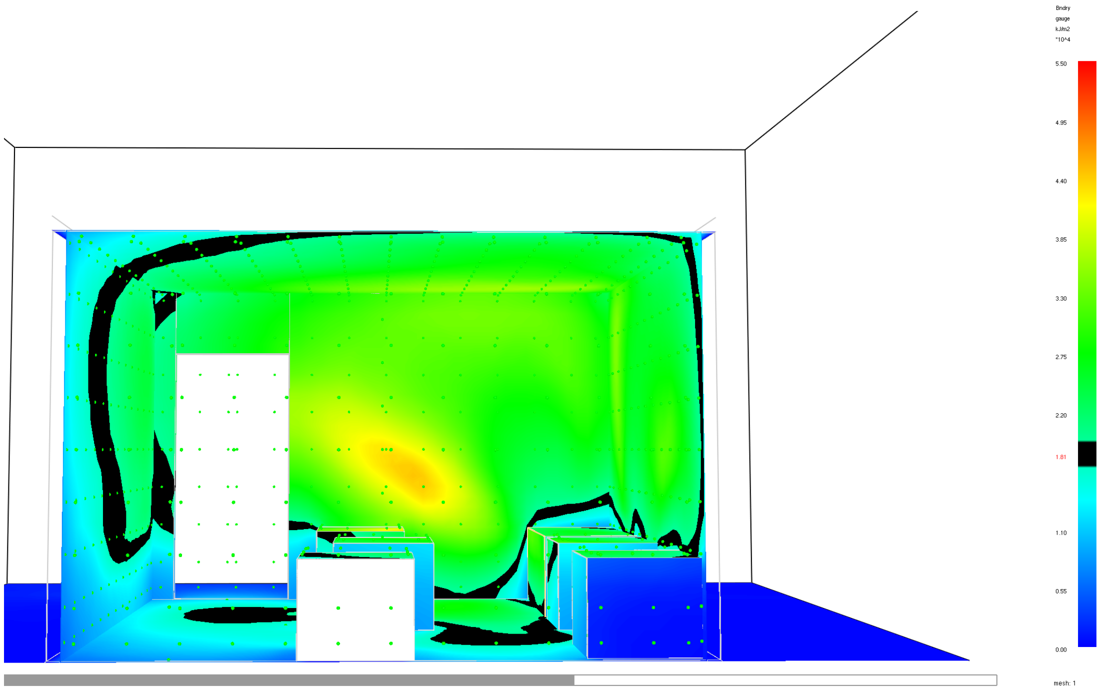
Figure D-4: Fire Position 1 1500kW-Smokeview Boundary File Time Integral Gauge Heat Flux (a) 18MJ/m² outlined at 960s (b) 39 MJ/m² outlined at 1000s

The 3000kW and 4000kW simulations became ventilation-controlled between 250-300 seconds. The location and magnitude of the time integral net heat flux for the 3000kW and 4000kW fires did deviate from the true origin. The location and magnitude of the heat flux from these fires was similar to each other, but varied greatly from their lower peak heat release rate counterparts (Compare Figures D-3, D-4 and Figures D-5, D-6). The location and magnitude of the heat flux begins to depart from the actual origin at approximately 180 seconds after the compartment becomes ventilation-controlled (~480s into the simulation). Figure D-7 depict the changes between the various time steps.

(a)


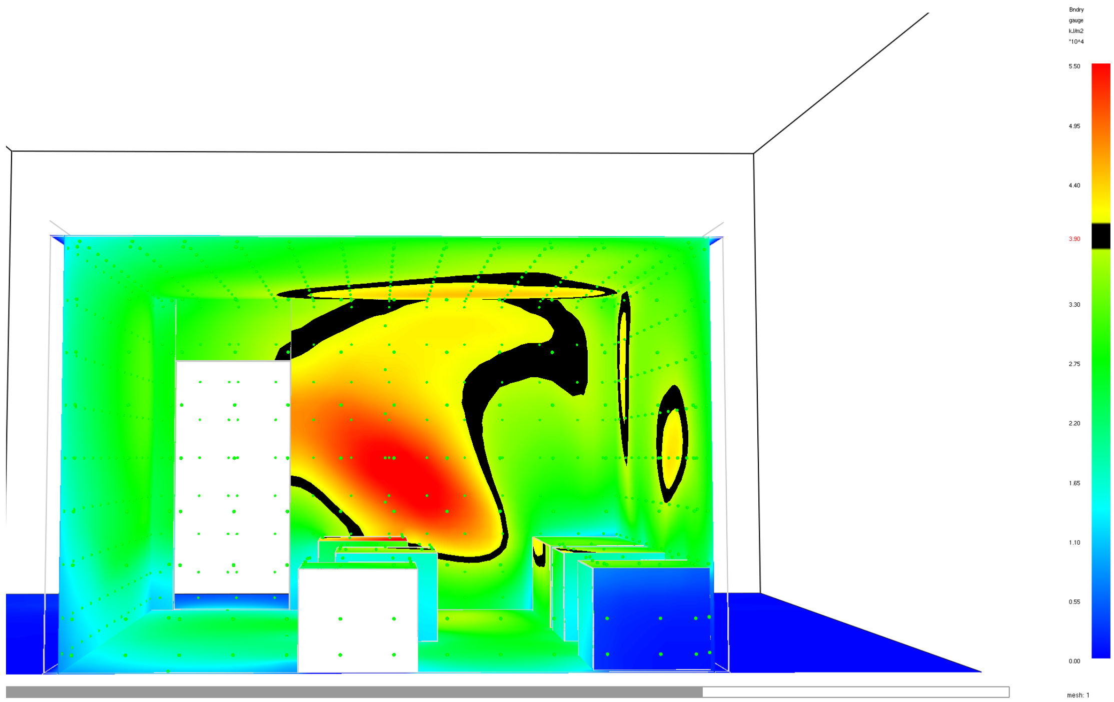


(b)

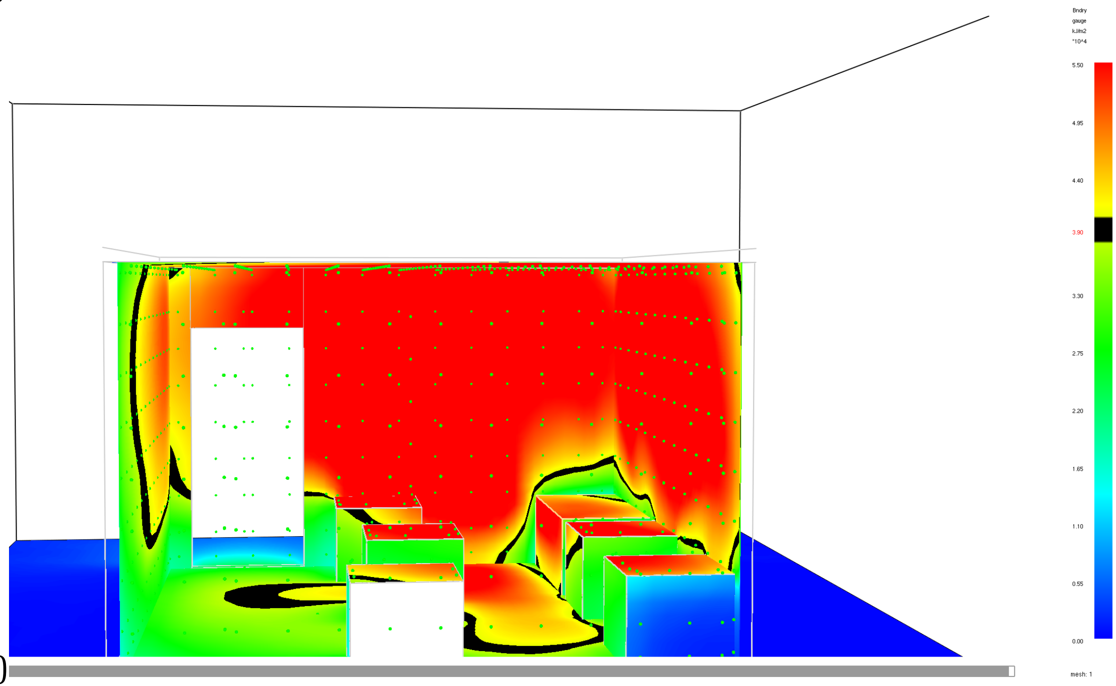


(c)

Figure D-5: Fire Position 1 4000kW-Smokeview Boundary File Time Integral Gauge Heat Flux (a) 18MJ/m² outlined at 405s (b) 18 MJ/m² outlined at 460s (c) 18 MJ/m² outlined at 650s



(a)



(b)

Figure D-6: Fire Position 1 4000kW-Smokeview Boundary File Time Integral Gauge Heat Flux (a) 39MJ/m² outlined at 750s (b) 39 MJ/m² outlined at 995s

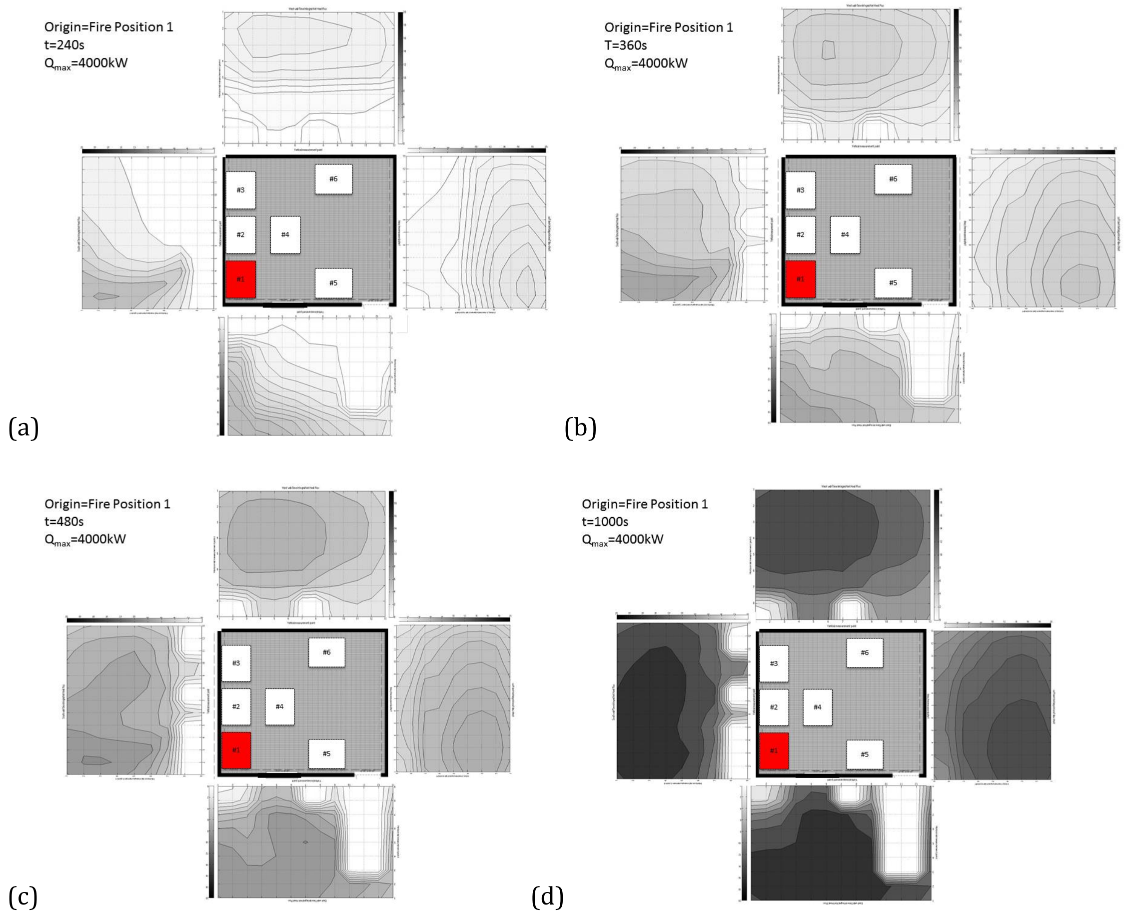
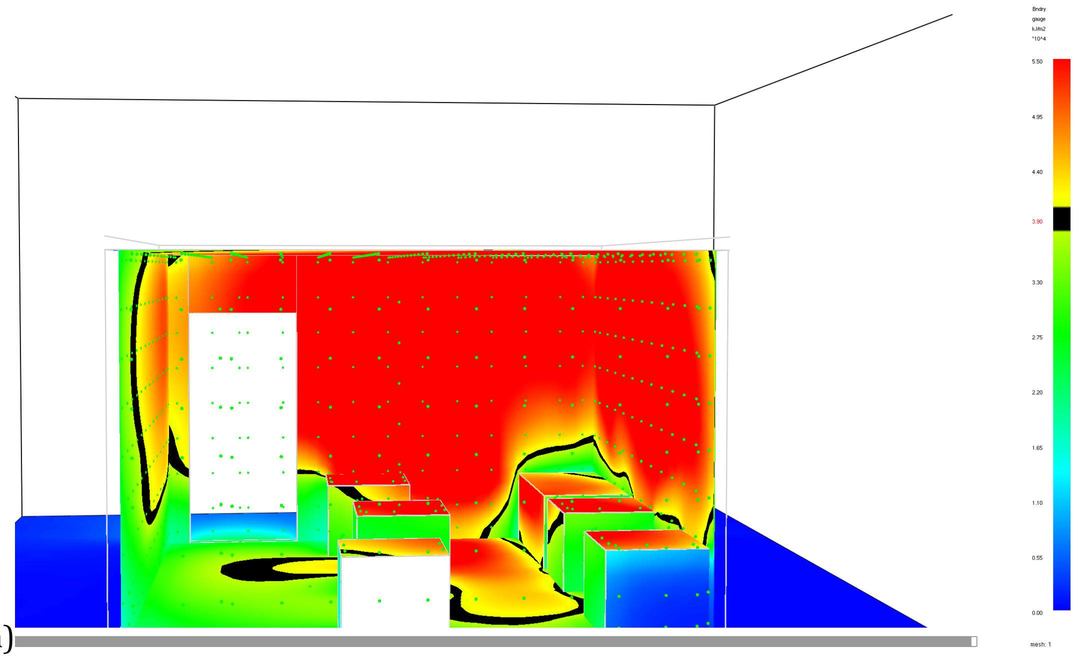
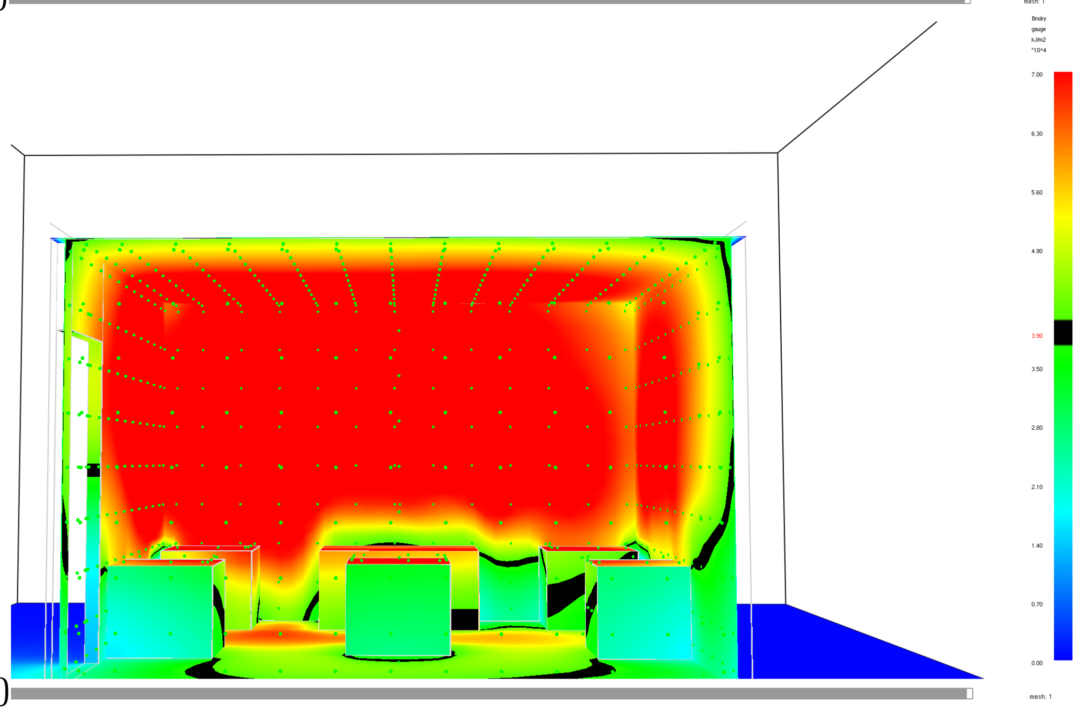


Figure D-7: Exploded view diagrams of Contour Plots of Time Integral Gauge Heat Flux at various time steps for fire position 1 (a) 240s (b) 360s (c) 480s (d) 1000s

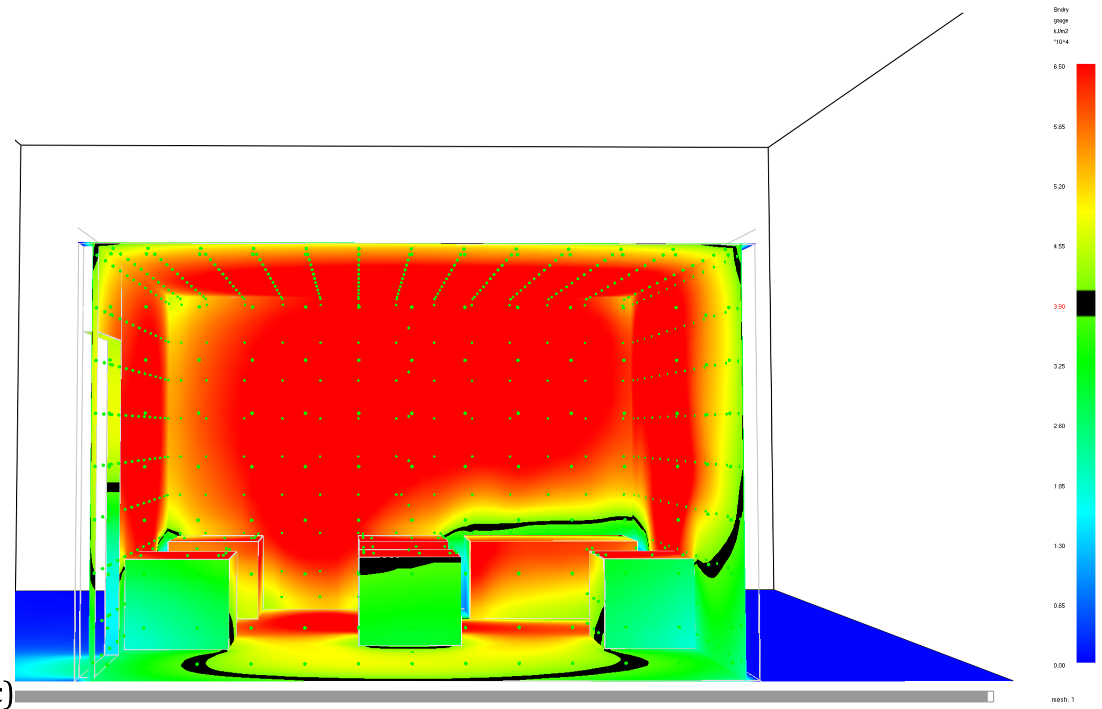
Comparing the wall contour plots for 1000 seconds for fire positions 1-4, the total heat fluxes within the compartments begin to become too similar to differentiate (Figure D-8). In other words, had the fire originated in any of these four locations, the location and magnitude of the total heat flux would be approximately the same and would provide no discernable difference. The contents, however, appear to provide directional heating still consistent with the area of origin.


Bndry
gauge
kJ/m2
*10^4
5.50
4.95
4.40
3.90
3.30
2.75
2.20
1.65
1.10
0.55
0.00
mesh: 1

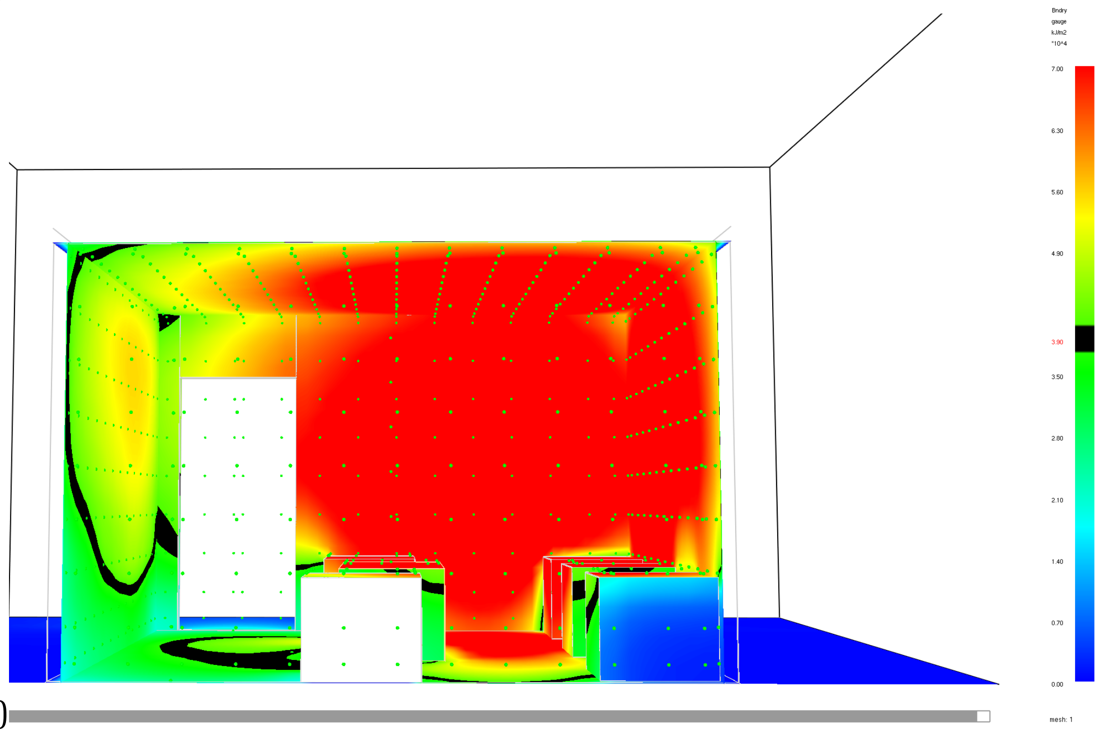
(a)


Bndry
gauge
kJ/m2
*10^4
7.00
6.30
5.60
4.90
3.90
3.50
2.80
2.10
1.40
0.70
0.00
mesh: 1

(b)



(c)



(d)

Figure D-8: 4000kW-Smokeview Boundary File Time Integral Gauge Heat Flux at 1000s (a) fire position 1 (b) fire position 2 (c) fire position 3 (d) fire position 4

References

Mann D, Putaansuu N (2009) Studies of the Dehydration/Calcination of Gypsum Wallboard. Paper presented at the Fire and Materials 2009 Conference, Interscience Communications, London (UK)
Mealy C, Gottuk D (2012) A Study of Calcination of Gypsum Wallboard. Paper presented at the International Symposium on Fire Investigations, Investigations Institute, Florida (USA)
Mealy C, Wolfe A, Gottuk D (2013) Forensic Analysis of Ignitable Liquid Fuel Fires in Buildings. Grant No. 2009-DN-BX-K232, Department of Justice (USA)
Mealy C (2013) Ignitable Liquid Fuel Fires in Buildings – A Study of Fire Dynamics. Grant No. 2009-DN-BX-K232, Department of Justice (USA)

APPENDIX E – Bayesian Networks and Probabilistic Inference

E.1 A Prototype of Identifying Relationships of Fire Pattern Generation with Bayesian Networks and Probabilistic Inference

Probabilistic inferences were developed between characteristics of the locations and trends of fire damage in relationship to the predominant factors associated with compartment fire dynamics. Bayesian theory has been put forward as a coherent model for interpreting forensic evidence (Taroni, et. al, 2006). Bayesian networks (BN) will be used to construct coherent, credible and defensible arguments in reasoning about the evidential value of the scientific evidence. A Bayesian network is a graphical model whose elements are nodes, arrows between nodes, and probability assignments. A predetermined set of nodes grouped together with a set of arrows or directed links between nodes forms a mathematical structure called a directed graph (Taroni, et. al, 2006). Bayesian networks are commonly defined as (Neapolitan, 1990):

- A set V=X_1, …, X_n of random variables, such that each variable X_b takes a set of exhaustive and mutually exclusive values. These variables will be represented as nodes in the network.
- A set E of probabilistic relationships between the variables. These relationships will be represented as arrows in the network.
- A joint probability distribution Pr, defined in V (where $Pr(x_1,\dots, x_n)$ denotes the probability that $X_1=x_1$, and … and $X_n=x_n$).

such that:

- The graph $G=(V, E)$ is a directed acyclic graph (DAG),
- The set (V, Pr) satisfies the conditional independence assumption.

In other words, A BN is a directed acyclic graph or DAG (V_b, E_b), where $\boldsymbol{V_b}$ is a set of nodes and $\boldsymbol{E_b}$ is a set of edges or arcs, and a set of conditional probability tables (CPTs), one for each node. Each node $V \in \boldsymbol{V_b}$ corresponds to a variable with a domain of mutually exclusive values $\boldsymbol{D_v}$. As such, the term node and variable of a BN can be used interchangeably (Keppens, 2012). The variable V in the BN is assigned exactly one of the values $v_i \in \mathbf{D_v}$ of its domain. Independence relations between nodes are defined through the edges of the DAG of the BN. This is through the assumption of the Markov condition, which states given truth values for the immediate parents of any node V in the BN, V is independent from any combination of other nodes in the network excluding its own descendants (Corfield & Williamson, 2001).

A conditional probability table establishes the probability distributions of the variable it is associated with, one for each combination of value assignments of its parents. This combined with the Markov condition permit a joint probability distribution to be calculated:

$$Pr: \quad \boldsymbol{D_{v_1}} \times \dots \times \boldsymbol{D}_{v_n} \rightarrow [0,1]:$$
$$(v_1, \dots, v_n) \rightarrow Pr(V_1: v_1, \dots, V_n: v_n)$$

where $\boldsymbol{V_b}$={V_1,..., V_n} and $v_i \in \boldsymbol{D}_{V_i}$. Thus, a BN can be defined by a tuple $\langle \boldsymbol{V}_b, \boldsymbol{E}_b, Pr \rangle$, where $\langle \boldsymbol{V}_b, \boldsymbol{E}_b \rangle$ defines a DAG, each $V \in \boldsymbol{V}_b$ possesses a domain $\mathbf{D_v}$ and Pr defines a probability distribution as above.

Bayesian analysis of forensic evidence first formulates two hypotheses (H_1 and H_2) that are to be contrasted with one another by means of the available evidence (E). These hypotheses correspond to a working hypothesis put forward by investigators and the best alternative explanation. The likelihood ratio LR is calculated by comparing the probability of the evidence under H_1 with that under H_2:

$$LR = \frac{Pr(E|H_1)}{Pr(E|H_2)}$$

If the LR >1, the probative value of evidence E is in favor of H_1, if LR<1 then E is in favor of H_2, and if LR=1 then it is said that E is not relevant for the hypotheses in question, or that the evidence is 'neutral' with respect to them (Taroni, et. al, 2006). Typically reported in evidential reasoning is that if the LR is calculated to be well above 1, on the order of 100, 1000, or 10,000 it is considered to be moderate to very strongly "*consistent with*" hypothesis 1, compared to hypothesis 2. On the other hand, if the LR results are closer to 0, on the order of 0.01, 0.001, and 0.0001 then the evidence is considered to be moderately to very strongly "*consistent with*" hypothesis 2, compared to hypothesis 1 (Keppens, 2012).

The effect of the evidence on hypotheses can be calculated by multiplying the LR by the prior odds.

$$\frac{Pr(H_1|E)}{Pr(H_2|E)} = LR \times Prior\ odds = \frac{Pr(E|H_1)}{Pr(E|H_2)} \times \frac{Pr(H_1)}{Pr(H_2)}$$

An example of using a BN for evidential reasoning can be found in Figure 17 (Keppens, 2012). Figure 17 is a DAG with four nodes labeled H, T, S, and E. These nodes describe features that are relevant to a scenario where a suspect has broken a window. H represents the hypothesis that the suspect is guilty of the crime, T is the transfer of glass fragments from window to the suspect's clothing, S represents whether a sufficient period of time has elapsed where fragments could have been lost, and E is the discovery of glass fragments matching the window in the suspect's clothing. All variables have Boolean domains ({true, false}). In this example, the assignment of V is v for true and $\bar{v}$ for false. This example is for illustrative use only, but is representative of an evidential reasoning BN (Keppens, 2012).

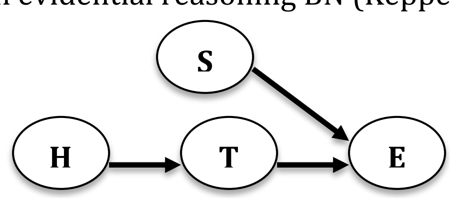


Figure 1: DAG of a simple representation of an evidential reasoning BN

A sample conditional probability table (CPT) for this DAG is shown in Table 7. The hypothesis under review is represented by a root node (H) in the BN, and the evidence by a leaf node (E). The edges represent causal relations in that committing the crime (H) causes glass fragments to end up in the perpetrator's clothes (T), and this may be discovered as evidence (E), even though the likelihood of the latter is reduced if a substantial amount of time has elapsed between the crime and evidence collection (Keppens, 2012).

Table 0-1: Sample CPTs for the simple BN example

	h			$\bar{h}$
Pr(t|H)	0.9			0.01
Pr($\bar{t}$|H)	0.1			0.99
	t		$\bar{t}$	
	s	$\bar{s}$	s	$\bar{s}$
Pr(e|T, S)	0.3	0.9	0	0
Pr($\bar{e}$|T, S)	0.7	0.1	1	1

Using the CPT values from table 7, the conditional probabilities can be calculated, such as:

$$Pr(e|h,s) = \sum_{T} Pr(e|T,s) \times Pr(T|h) = 0.3 \times 0.9 + 0 \times 0.1 = 0.27$$

and

$$Pr\left(e\middle|\bar{h},s\right) = \sum_{T} Pr(e|T,s) \times Pr\left(T\middle|\bar{h}\right) = 0.3 \times 0.01 + 0 \times 0.99 = 0.003$$

The likelihood ratio for this example would be calculated as such:

$$\frac{Pr(e|h,s)}{Pr\left(e\middle|\bar{h},s\right)} = \frac{0.27}{0.003} = 90$$

Based on these calculations and the simple BN, it can be argued that the discovery of glass fragments on a suspect's clothing a substantial time after a crime has been committed, is moderately more consistent with the hypothesis that the suspect is guilty than the hypothesis that the suspect is innocent.

A similar approach to using probabilistic inference and Bayesian networks is proposed here for evaluating the cause of fire patterns conditional on the compartment fire dynamics and damage characteristics identified.

E.1.1 Identification of Prior Probabilities

It is proposed that the prior probabilities should have input from both the predictive aspect of fire pattern causes (i.e. fire dynamics) and the evidence that remains after the fire (i.e. damage). The predictive aspect relates to the use of a few currently accepted engineering calculations and studies regarding compartment fire dynamics to establish thresholds and relationships, including flashover correlations and distances for radiant heat damage to occur. Each of these will be described in the next sections.

To evaluate the evidence that remains after a fire, seventy full-scale fire pattern studies were reviewed (Claflin, 2013; Gorbett, et. al, 2008; Gorbett, et. al, 2010; Gorbett, et. al, 2013; Hoffmann, et. al, 2003; Cox, 2013; Mealy & Gottuk, 2012; Mealy, Wolfe & Gottuk, 2013; Oulette, 2008; Shanley, 1997). To the author's knowledge this is an exhaustive list of empirical studies addressing fire patterns. A database of these seventy tests was developed, in which the known compartment fire dynamics characteristics and identified common damage characteristics were catalogued. The damage characteristics were labeled as damage cues and numbered for ease of classification. Damage cues are characteristics of damage noted by the fire pattern literature as being a characteristic that assisted investigators in interpreting the cause of the damage. An example of a damage cue for determining if flashover occurred is "damage low in elevation throughout the entire compartment". Each study was then evaluated for each damage cue that may assist the investigator in determining the burning regime, plume-generated, ventilation-generated, upper layer-generated, and alternative fire pattern causes. This data set, in conjunction with the characteristics of fire dynamics, serves to calculate the prior probabilities. Each of these prior probabilities and damage cues will be described in the next sections.

In this study a software package was used to construct the networks and perform the likelihood ratio and posterior probability calculations. This study uses HUGIN Version 7.8 (http://www.hugin.com).

E.1.2 Burning Regime Determination

The accurate identification and evaluation of the potential causative heat sources becomes conditionally dependent first on the correct identification of the burning regime. Consequently, the first step to accurately relate damage to potential heat sources requires the analyst to determine which burning regime existed. The burning regime decision is either fuel-controlled or ventilation-controlled. Flashover was distinguished as the element to differentiate with certainty between fuel-controlled and ventilation-controlled conditions. The review of fire pattern studies found that 45 of the 70 (64%) full-scale tests were ventilation-controlled, while 25 of 70 (36%) were fuel-controlled. The prior probabilities associated with the Burning Regime will be set at 60% ventilation-controlled and 40% fuel-controlled. The damage cues evaluated to determine ventilation-controlled or fuel-controlled conditions were:

- Cue 1-significant loss of mass to all combustibles throughout the compartment
- Cue 2-damage identified low in elevation throughout the entire compartment.
- Cue 3-witnesses identified sustained flaming on the exterior of the compartment.

Cues 1 and 2 were found to have a higher rating of accuracy in determining the burning regime. Of the studies reviewed, 42 out of 45 (93%) ventilation-controlled fires had damage cues 1 and 2 identified positively, while only 3 out of 25 (12%) fuel-controlled studies were falsely identified as being ventilation-controlled. The three tests that were falsely identified were close to reaching flashover conditions, but were manually extinguished immediately before flashover. Therefore, this finding supports that cue 1 and 2 can be used as damage cues to help determine the burning regime. Based on this analysis, the prior probabilities for both cues will be set at 90% if true and 10% if false for ventilation-controlled.

Several flashover correlations can also be conducted to help predict whether the compartment will flashover given the estimated heat release rates of the fuels

($\dot{q}$), total surface area (A_T), and the ventilation factor ($A_v\sqrt{h_v}$). The flashover correlations selected to compare to the results identified in the fire pattern studies were the methods of Babrauskas, Thomas, and MQH (Babrauskas, 1980; McCaffrey, Quintiere & Harkleroad, 1981; Thomas, 1981). One limitation with using the database for predicting flashover was that only 32 of the studies had total heat release rate data or heat release rate data for the initial fuels. The other 38 studies where heat release rate data was not available were estimated based on the initial fuel burning. This estimation methodology, while containing significant uncertainty, would be more consistent with actual fire investigations. It was found that the flashover correlations correctly predicted flashover (i.e. ventilation-controlled conditions) for all of the ventilation-controlled fires (45/45). However, this method over predicted that flashover would occur in 56% (14/25) of those fires that did not transition to ventilation-controlled conditions. Due to the uncertainty associated with the predicting flashover from estimated values, a prior probability for flashover to occur based on calculations was determined to be 50%.

The conditional probability tables, model variables, and the initial state for the BN to determine the burning regime in a compartment is based on the flashover correlations and the two damage cues (Figures 18-20, Table 8). The initial state illustrates the model's parameters before any evidence is introduced and reflects the calculated likelihood ratio for each node (Figure 20). The CPTs list the prior probabilities for all variables (Figure 19). As evidence is introduced, the initial state evolves into posterior probabilities based on the type of evidence identified. All variables have Boolean domains ({true, false}). The burning regime analysis would need to be done first before fire pattern 1-*n* are evaluated through the fire pattern generation step.

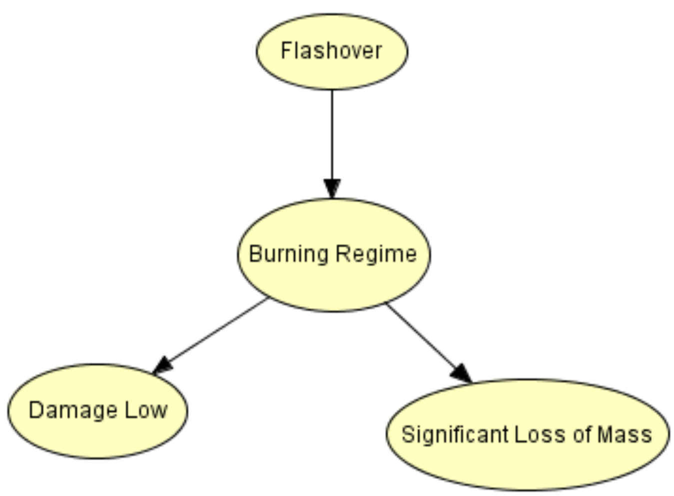


Figure 2: BN for Determining the Burning Regime for a Compartment Fire

Table 0-2: Variables for the Burning Regime BN

Variable	Meaning
BR	Burning regime

f.c.	Fuel-controlled
v.c	Ventilation-controlled
Flashover	Flashover
DL	Damage Low
LM	Significant Loss of Mass

Flashover(Flashover)

Predicted	0.5
Not Predicte	0.5

Burning Regime(BR)

Flashover	Predicte	Not Pred
f.c.	0.4	0.6
v.c.	0.6	0.4

Damage Low(DL)

BR	f.c.	v.c.
true	0.1	0.9
false	0.9	0.1

Significant Loss of Mass(LM)

BR	f.c.	v.c.
true	0.1	0.9
false	0.9	0.1

Figure 3: CPTs for Burning Regime Determination

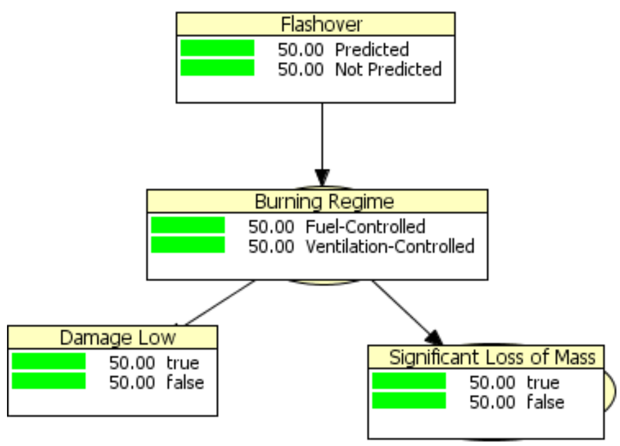


Figure 4: Probability Distribution for Initial State LR's for Determining Burning Regime BN

All evolutions for this BN will be shown here to serve as an introduction to evidential reasoning with the identification of certain evidence and its influence on the posterior probabilities. Other sections of this report will not detail all evolutions.

The first evolution evaluated is the updating of the model when evidence of flashover or not flashover is introduced (Figure 21). Figure 21 (a) introduces the evidence that flashover has been predicted based on the flashover correlations compared to the A_T, $\dot{q}$, and $A_v\sqrt{h_v}$ for this scenario. Note that the posterior probabilities for the burning regime variable have been updated to 60% ventilation-controlled and 40% fuel-controlled. Correspondingly, the posterior probabilities have been updated for the potential identification of the damage cues as well. However, Figure 21 (b) illustrates the impact of not predicting flashover.

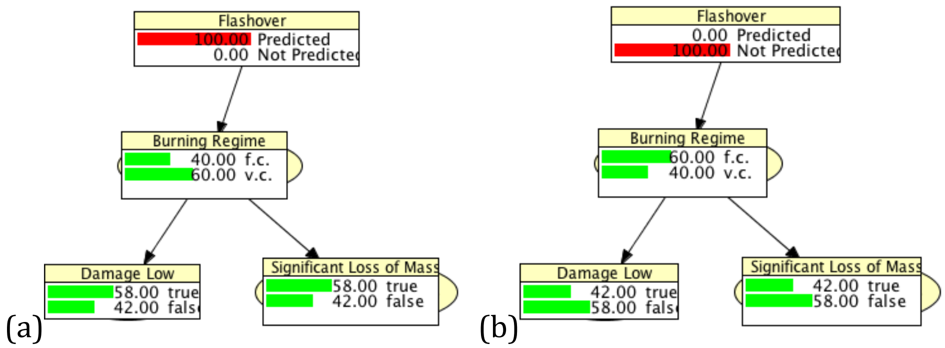


Figure 5: Probability distributions associated with the flashover variable at different stages of inference (a) flashover predicted, (b) flashover not predicted

If the flashover node is predicted and one of the damage cues are identified as true, then the posterior probabilities of the burning regime and the potential to find the secondary damage cue are increased (Figure 22 (a)). If the flashover node is predicted and both damage cues are identified as true, then the posterior probability of the burning regime is strongly consistent with a ventilation-controlled fire (Figure 22 (b)). Regardless which damage cue was selected, the change to the burning regime posterior probabilities would be the same for either one of them selected.

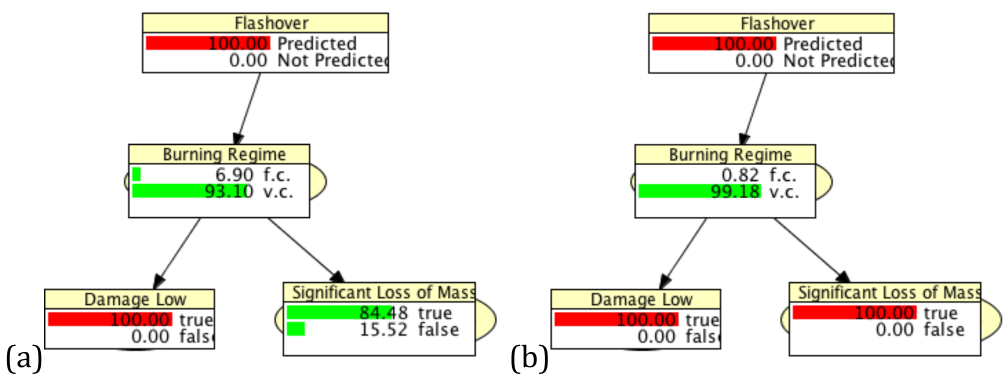


Figure 6: Probability distribution with the flashover variable and one damage cue (a) flashover predicted + damage low true, (b) flashover predicted + both damage cues true

If the flashover node is not predicted, but a damage cue is identified as true then the influence of the damage cue(s) is still greater on the burning regime due to the prior weighting. Therefore, if flashover is not predicted and one or more of the damage cues are identified, then the burning regime posterior probability is still strongly consistent with a ventilation-controlled fire (Figure 23).

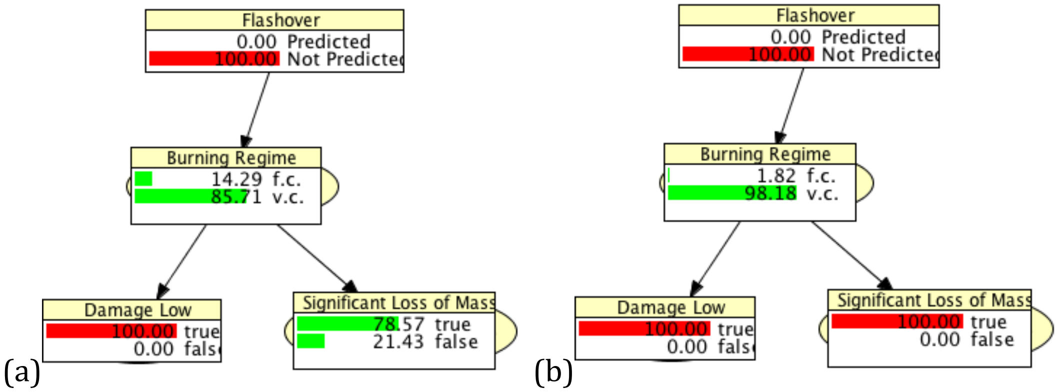


Figure 7: Probability distribution with the flashover variable not predicted and damage cues identified as true (a) flashover not predicted + damage low true, (b) flashover not predicted + both damage cues true

If the flashover node is not predicted, and the damage cue(s) are false the posterior probability is strongly consistent with a fuel-controlled fire (Figure 24).

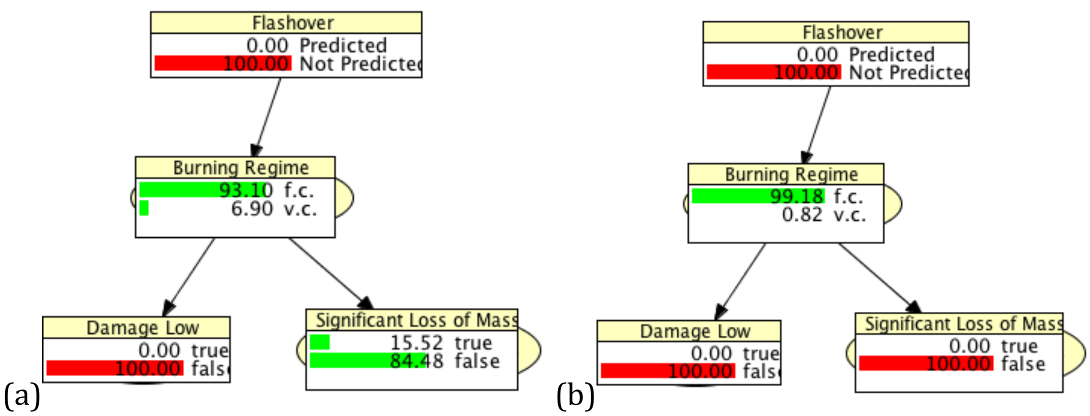


Figure 8: Probability distribution with the flashover variable not predicted and damage cues identified as false (a) flashover not predicted + damage low false, (b) all false

If flashover is predicted, but the damage cue(s) is identified as false, the posterior probability is strongly consistent with a fuel-controlled fire (Figure 25).

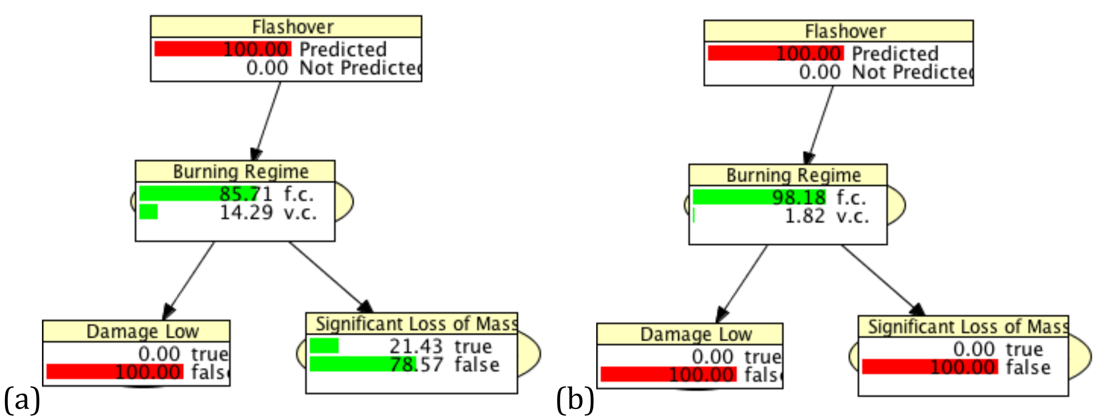


Figure 9: Probability distribution with the flashover variable predicted and damage cues identified as false (a) flashover predicted + damage low false, (b) flashover predicted + both damage cues false

Figure 26 (a) illustrates if one damage cue is identified as true, then the posterior probability of the burning regime would be moderately consistent with a ventilation-controlled fire. However, if one damage cue is identified as false, then the burning regime would be moderately consistent with a fuel-controlled fire (Figure 26 (b)).

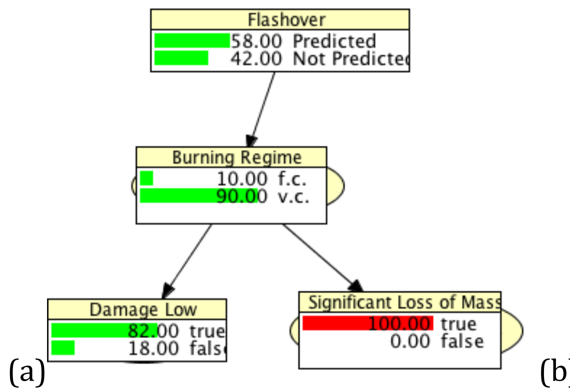


Figure 10: Probability distribution with the damage cue only (a) significant loss of mass was identified as true, (b) significant loss of mass not identified.

If both damage cues are identified as false, then the burning regime would be strongly consistent with a fuel-controlled fire (Figure 27 (a)). If both damage cues are identified as true, then the burning regime would be strongly consistent with a ventilation-controlled fire (Figure 27 (b)).

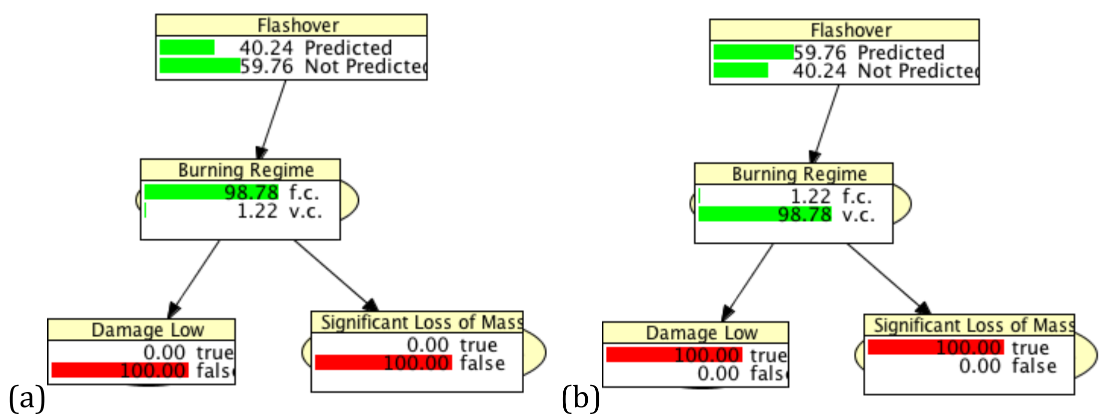


Figure 11: Probability distribution with both damage cues (a) false, (b) true

If one damage cue is identified as true and the other as false, then the evidence is considered neutral (Figure 28 (a)). If the flashover variable is added, then it can be seen that the weight of this evidence permits the decision to be swayed one way or the other (Figure 28 (b,c)).

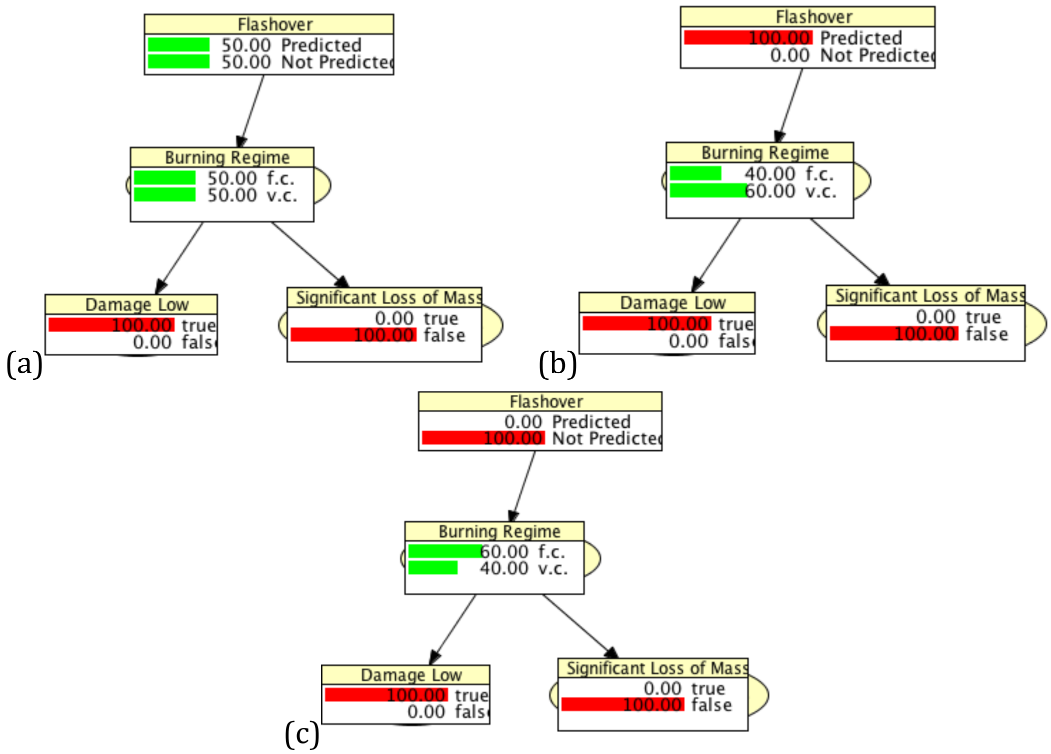


Figure 12: Probability distribution with one damage cue true and the other false (a) with no evidence regarding flashover, (b) with flashover predicted, (c) with flashover not predicted

After the burning regime has been classified as consistent with fuel-controlled or ventilation-controlled, each fire pattern (1-*n*) will be evaluated as to the generation of the fire pattern through 4.4.2.3-4.4.2.8.

E.1.3 Plume-Generated (PG) Fire Pattern

The prior probabilities in determining whether or not a fire pattern was created by a plume have been found to be conditional first on the burning regime. The fire pattern studies revealed that specific damage cues identified during fuel-controlled conditions were not as prevalent during ventilation-controlled conditions. Secondly, the distance of the fuel item in relationship to the affected surface influences the prior probabilities on whether or not the damage cues could be identified. Therefore, the two fire dynamics issues that should be considered in determining if a fire pattern was caused by a plume is the burning regime and the distance of the fuel item to the affected surface. The prior probabilities associated in identifying specific damage cues for fuel-controlled or ventilation-controlled conditions will be instituted into the probability distribution tables for their respective models.

The prior probabilities associated with the presence of a fuel and its distance from the affected surface is based on Babrauskas and Theobald's research (1981, 1968). Their research indicated that a burning fuel item located within 1.2 meters in horizontal distance from the surface would result in damage to that surface. Therefore, in this research the 1.2m distance will be used as a threshold for the prior probability associated with the potential of a fuel causing the plume-generated damage. If a fuel item is located within 1.2m from the fire pattern being evaluated, then the probability associated with that fire pattern being generated by a plume is 80%.

The damage cues evaluated for plume-generated damage included:

- Cue 1-loss of mass to fuel is consistent with damage to affected surface,
- Cue 2-increased magnitude of damage near the fuel item,
- Cue 3-elevation of the line of demarcation is consistent with the height of the fuel item,
- Cue 4-width of base of damage is approximately the width of the fuel item and not greater than two times the width of the fuel item,
- Cue 5-lines of demarcation are angled emanating from the fuel item, and
- Cue 6-sharp/distinct lines of demarcation near or appear to be emanating from the fuel item,
- Cue 7-conical shape.

The fuel-controlled conditions had consistent higher probabilities in positively identifying each cue as compared to ventilation-controlled conditions. In fuel-controlled conditions, cues 2-4 were positively identified in 92% of the studies (23/25), cues 1 and 5 were positively identified in 88% of the studies (22/25), cue 6 was positively identified in 84% of the studies (21/25), and cue 7 was identified in only 68% of the studies (17/25). In ventilation-controlled conditions, cue 1 was the most positively identified in 87% of the studies (39/45), cues 2-5 were identified in 76% of the studies (34/45), cue 6 was identified in 62% of the studies (28/45), and cue 7 was only identified in 42% of the studies (19/45). Given these findings, damage cues 1-5 are used as the most accurate damage cues for classifying a fire pattern generated by a plume.

The conditional probability tables, model variables, and the initial state for the BN are based on the five damage cues and a fuel item present in order to determine if the fire pattern can be classified as being caused by a plume (Figures 29-33, Table 9). The initial state illustrates the model's parameters before any evidence is introduced and reflects the calculated likelihood ratio for each node (Figure 29 & 32). The conditional probability tables list the prior probabilities for all variables conditional on fuel-controlled and ventilation-controlled conditions (Figures 31 & 33). As evidence is introduced, the initial state evolves into posterior probabilities based on the type of evidence identified. All variables have Boolean domains ({true, false}). This analysis would be performed with all fire patterns identified (1-*n*).

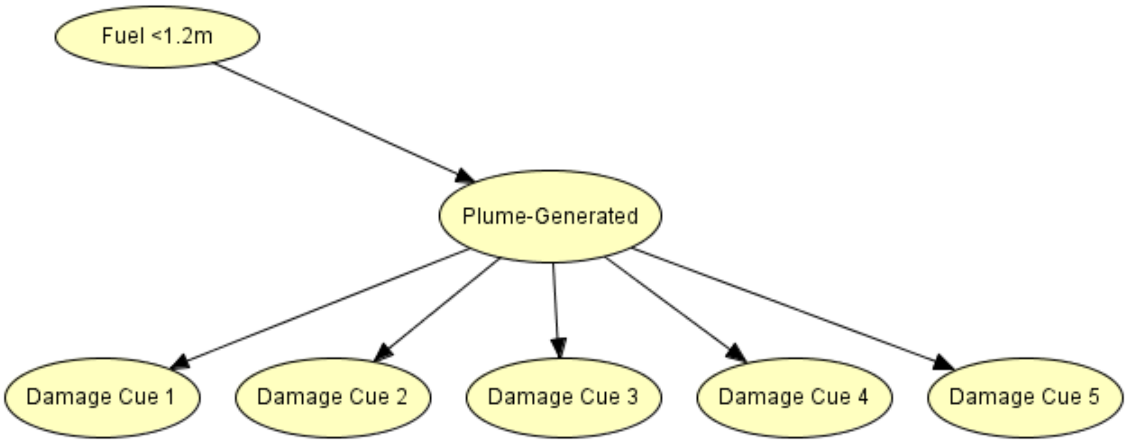


Figure 13: BN for Determining if the Fire Pattern was Plume-Generated

Table 0-3: Variables for Plume-Generated BN

Variable	Meaning
PG	Plume-Generated
Fuel <1.2m	Fuel present and less than 1.2 m
Damage Cue 1	Loss of mass to fuel is consistent with damage to affected surface
Damage Cue 2	Increased magnitude of damage near fuel item
Damage Cue 3	Elevation of the line of demarcation is consistent with the height of the fuel item
Damage Cue 4	Width of the base of damage is approximately the width of the fuel item and no greater than 2 times the width of the fuel
Damage Cue 5	Lines of demarcation are angled emanating from the fuel item

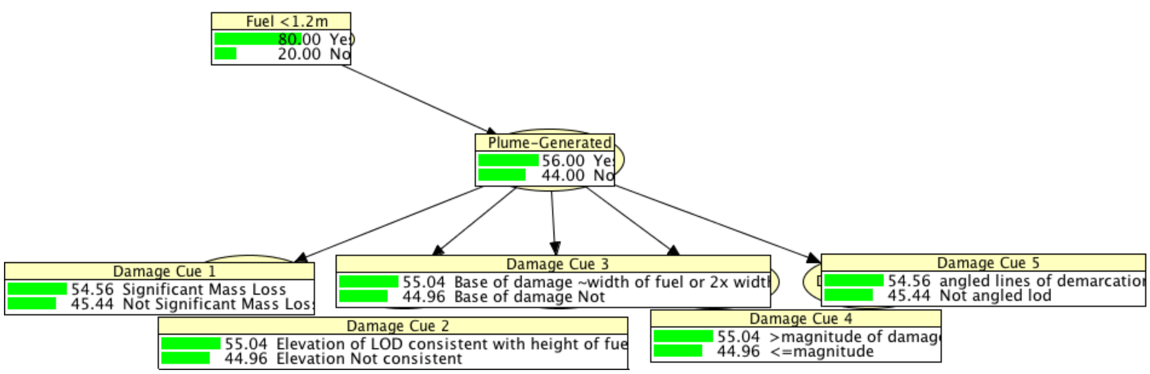
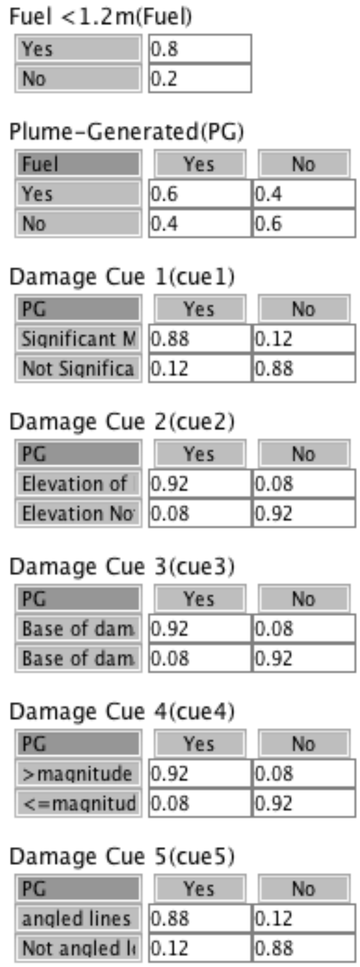


Figure 14: Probability Distribution of the Initial Conditions for Fuel-Controlled Plume-Generated BN



Fuel <1.2m(Fuel)

Yes	0.8
No	0.2

Plume-Generated(PG)

Fuel	Yes	No
Yes	0.6	0.4
No	0.4	0.6

Damage Cue 1(cue1)

PG	Yes	No
Significant M	0.88	0.12
Not Significa	0.12	0.88

Damage Cue 2(cue2)

PG	Yes	No
Elevation of	0.92	0.08
Elevation No	0.08	0.92

Damage Cue 3(cue3)

PG	Yes	No
Base of dam	0.92	0.08
Base of dam	0.08	0.92

Damage Cue 4(cue4)

PG	Yes	No
>magnitude	0.92	0.08
<=magnitud	0.08	0.92

Damage Cue 5(cue5)

PG	Yes	No
angled lines	0.88	0.12
Not angled l	0.12	0.88

Figure 15: Plume-Generated CPT for Fuel-controlled Conditions

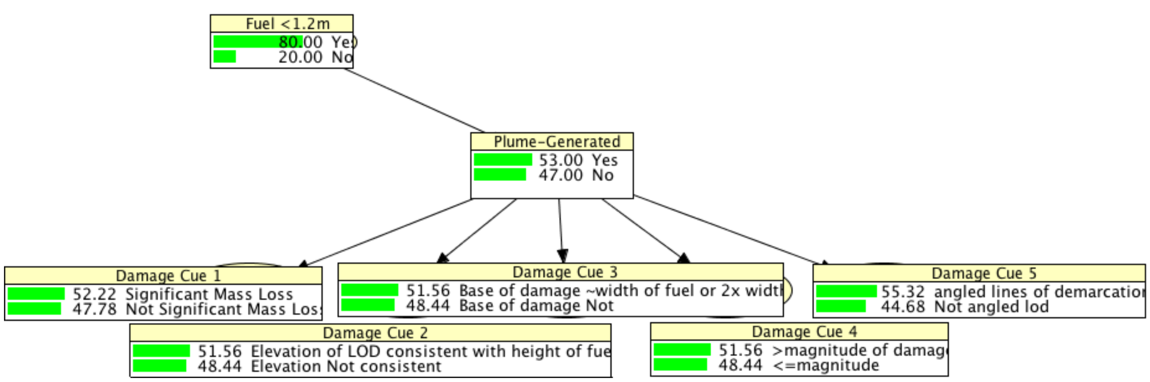


Figure 16: Probability Distribution of the Initial Conditions for Ventilation-Controlled Plume-Generated BN

Fuel <1.2m(Fuel)

Yes	0.8
No	0.2

Plume-Generated(PG)

Fuel	Yes	No
Yes	0.55	0.45
No	0.45	0.55

Damage Cue 1(cue1)

PG	Yes	No
Significant M	0.87	0.13
Not Significa	0.13	0.87

Damage Cue 2(cue2)

PG	Yes	No
Elevation of	0.76	0.24
Elevation No	0.24	0.76

Damage Cue 3(cue3)

PG	Yes	No
Base of dam	0.76	0.24
Base of dam	0.24	0.76

Damage Cue 4(cue4)

PG	Yes	No
>magnitude	0.76	0.24
<=magnitud	0.24	0.76

Damage Cue 5(cue5)

PG	Yes	No
angled lines	0.76	0.24
Not angled l	0.24	0.51

Figure 17: Plume-Generated CPT for Ventilation-controlled Conditions

E.1.4 Ventilation-Generated (VG) Fire Pattern

The prior probabilities in determining whether or not a fire pattern was created by ventilation have been found to be conditional first on the burning regime. The fire pattern studies revealed that ventilation virtually never causes any damage of significance during fuel-controlled conditions. However, ventilation becomes one of the more prominent influences of damage when the compartment has transitioned into ventilation-controlled conditions. The presence of a ventilation opening is necessary. Door openings to the exterior were identified as being the most influential to damage.

The damage cues evaluated for plume-generated damage included:

- Cue 1- increased area and magnitude of damage within the airflow from the opening,
- Cue 2-increased area and magnitude of damage across from the opening,

- Cue 3-increased magnitude of damage around opening within 2 times the opening width ($2w_v$),
- Cue 4-lines of demarcation are angled emanating from the ventilation opening,
- Cue 5-increased area and magnitude of damage under the window, and
- Cue 6-increased area and magnitude of damage around gypsum wallboard seams.

The fuel-controlled conditions did not have any damage associated with ventilation openings, therefore it will not be considered here. In ventilation-controlled conditions, cue 1 was the most positively identified in 82% of the studies (37/45), cue 2 was identified in 73% of the studies (33/45), cue 4 was identified in 64% of the studies (29/45), cue 6 was identified in 62% of the studies (28/45), cue 3 was identified in 53% of the studies (24/45), and cue 5 was only identified in 11% of the studies. Given these findings, damage cues 1, 2, and 3 are used as the most accurate damage cues for classifying a fire pattern generated by ventilation. Cues 4 and 5 were identified more than cue 3, however, these were not used as damage cues due to their ambiguity.

The conditional probability tables, model variables, and the initial state for the BN to determine if the fire pattern can be classified as being caused by ventilation (Figures 34-36, Table 10). The initial state illustrates the model's parameters before any evidence is introduced and reflects the calculated likelihood ratio for each node (Figure 34). The conditional probability tables list the prior probabilities for all variables for ventilation-controlled conditions (Figure 36). As evidence is introduced, the initial state evolves into posterior probabilities based on the type of evidence identified. All variables have Boolean domains ({true, false}). This analysis would be performed with all fire patterns identified (1-*n*).

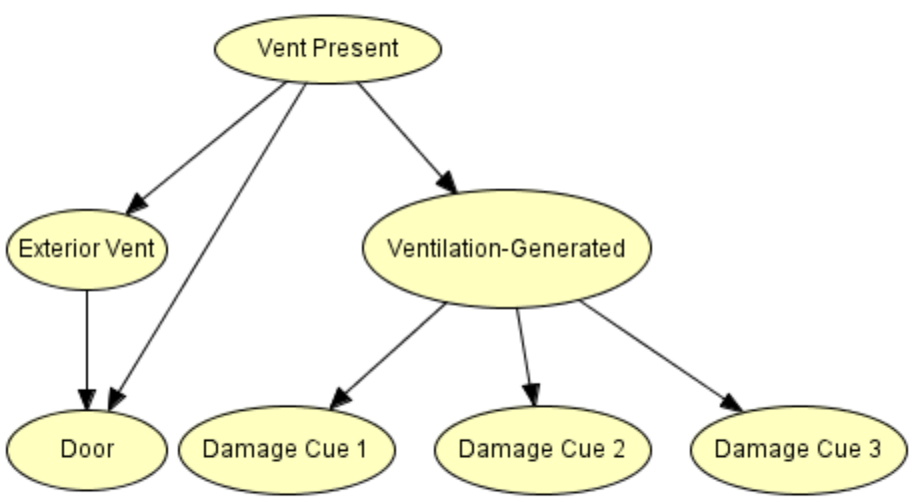


Figure 18: BN for Determining if the Fire Pattern is Ventilation-Generated

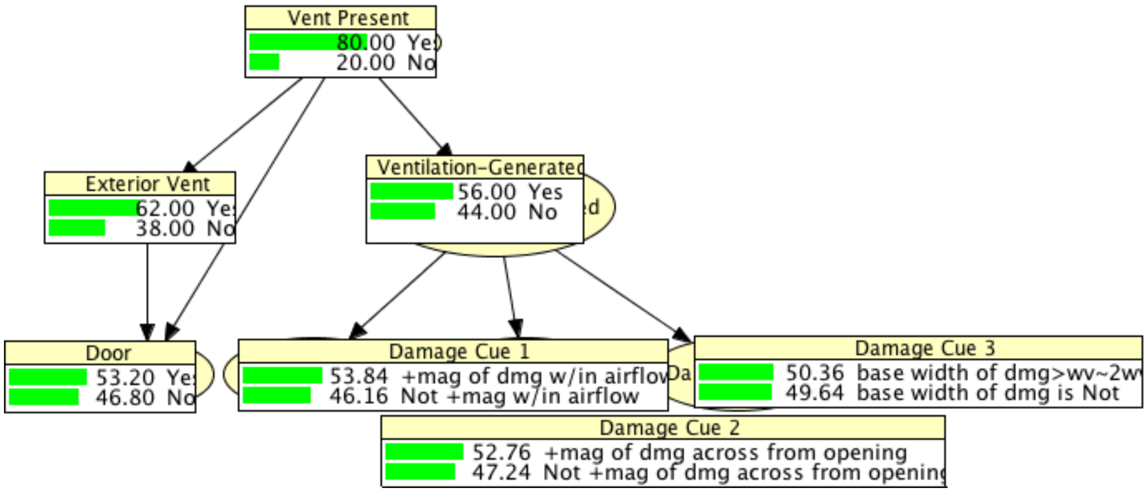


Figure 19: Probability Distribution Initial State for Determining Ventilation-Generated BN

Table 0-4: Variables for Ventilation-Generated BN

Variable	Meaning
VG	Ventilation-Generated
Vent Present	Vent Present?
Exterior Vent	Is the vent to the outside
Door	Is the vent a door
Damage Cue 1	Increased area and magnitude of damage within the airflow from the opening,
Damage Cue 2	Increased are and magnitude of damage across from opening
Damage Cue 3	Increased magnitude of damage of damage around opening within 2 times the opening width ($2W_v$)

Vent Present(Vent)

Yes	0.8
No	0.2

Exterior Vent(Exterior)

Vent	Yes	No
Yes	0.7	0.3
No	0.3	0.7

Door(Door)

Vent	Yes		No	
Exterior	Yes	No	Yes	No
Yes	0.6	0.4	0.5	0.5
No	0.4	0.6	0.5	0.5

Ventilation-Generated(PG)

Vent	Yes	No
Yes	0.6	0.4
No	0.4	0.6

Damage Cue 1(cue1)

PG	Yes	No
+mag of dm	0.82	0.18
Not +mag w	0.18	0.82

Damage Cue 2(cue2)

PG	Yes	No
+mag of dm	0.73	0.27
Not +mag of	0.27	0.73

Damage Cue 3(cue3)

PG	Yes	No
base width o	0.53	0.47
base width o	0.47	0.53

Figure 20: Ventilation-Generated CPT

E.1.5 Upper Layer Generated (ULG) Fire Pattern

The prior probabilities in determining whether or not a fire pattern was created by an upper layer have been found to be conditional first on the burning regime. The fire pattern studies revealed that the upper layer damage is very difficult to identify after the fire has transitioned into ventilation-controlled conditions. The presence of a soffit and the size of an opening influences the depth of the damage within the compartment, however, as the compartment nears flashover damage begins to occur low in elevation on all surfaces. This damage begins to obscure some of the earlier lines of demarcation from the upper layer.

The damage cues evaluated for plume-generated damage included:

- Cue 1-damage high in elevation on wall surfaces,
- Cue 2-uniform magnitude of damage,
- Cue 3- increasing lines of demarcation moving out of vent openings, and
- Cue 4- level lines of demarcation along all wall surfaces.

The ventilation-controlled conditions did not result any upper layer damage that was discernable, therefore it will not be considered here. In fuel-controlled conditions, cues 1 and 2 were the most positively identified in 80% of the studies (20/25), cue 3 was identified in 60% of the studies (15/25), and cue 4 was only identified in 48% of the studies (12/25). Given these findings, damage cues 1, 2, and 3 are used as the most accurate damage cues for classifying a fire pattern generated by upper layer.

The conditional probability tables, model variables, and the initial state for the BN to determine if the fire pattern can be classified as being caused by the upper layer (Figures 37-39, Table 11). The initial state illustrates the model's parameters before any evidence is introduced and reflects the calculated likelihood ratio for each node (Figure 38d). The conditional probability tables list the prior probabilities for all variables for fuel-controlled conditions (Figure 39). As evidence is introduced, the initial state evolves into posterior probabilities based on the type of evidence identified. All variables have Boolean domains ({true, false}). This analysis would be performed with all fire patterns identified (1-*n*).

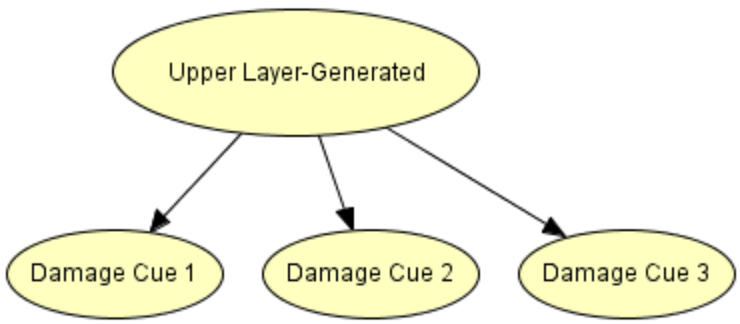


Figure 21: BN for Determining if Fire Pattern is Upper Layer-Generated

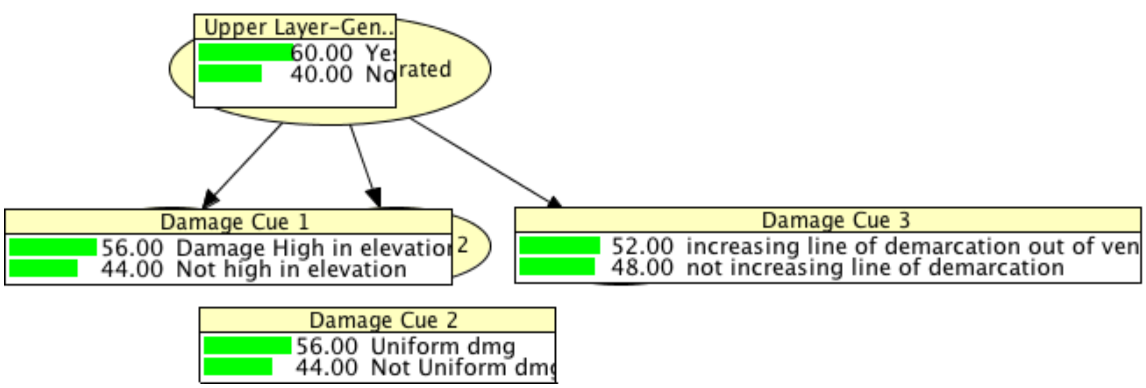


Figure 22: Probability Distribution Initial State for Determining Upper Layer-Generated BN

Table 0-5: Variables for Upper Layer-Generated BN

Variable	Meaning
ULG	Upper Layer-Generated
Damage Cue 1	Damage high in elevation
Damage Cue 2	Uniform magnitude of damage
Damage Cue 3	Increasing line of demarcation out of ventilation opening

Upper Layer–Generated(ULG)

Yes	0.6
No	0.4

Damage Cue 1(cue1)

ULG	Yes	No
Damage Higl	0.8	0.2
Not high in e	0.2	0.8

Damage Cue 2(cue2)

ULG	Yes	No
Uniform dmc	0.8	0.2
Not Uniform	0.2	0.8

Damage Cue 3(cue3)

ULG	Yes	No
increasing lii	0.6	0.4
not increasir	0.4	0.6

Figure 23: Upper Layer-Generated CPT

E.1.6 Suppression Generated (SG) Fire Pattern

Will not be addressed in this dissertation

E.1.7 Alternate Causal Factors

Will not be addressed in this dissertation.

E.1.8 Undetermined Generated (UKG) Fire Pattern

If the fire pattern generation cannot be conclusively determined, then the fire pattern generation is noted as undetermined.

APPENDIX F – Bayesian Networks Results for Fire Pattern Generation

Below are the fire pattern generation Bayesian networks for Fire Position #1

Fire Position 1, 1500 kW, 120 seconds

Fire Pattern 1 – Plume Generated:

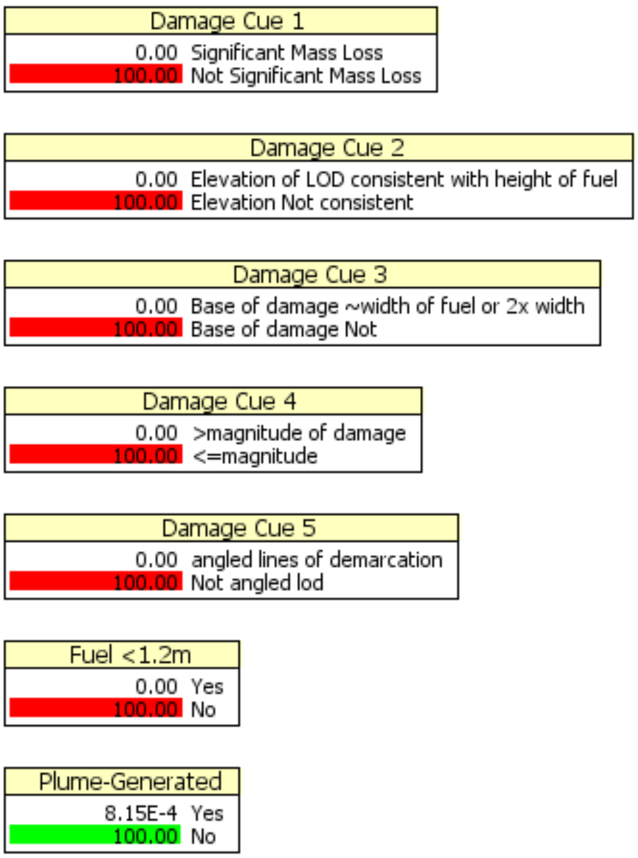


Figure F-1: FP1, 1500kW, 120 seconds, Fire Pattern 1, Plume Generated Probabilities

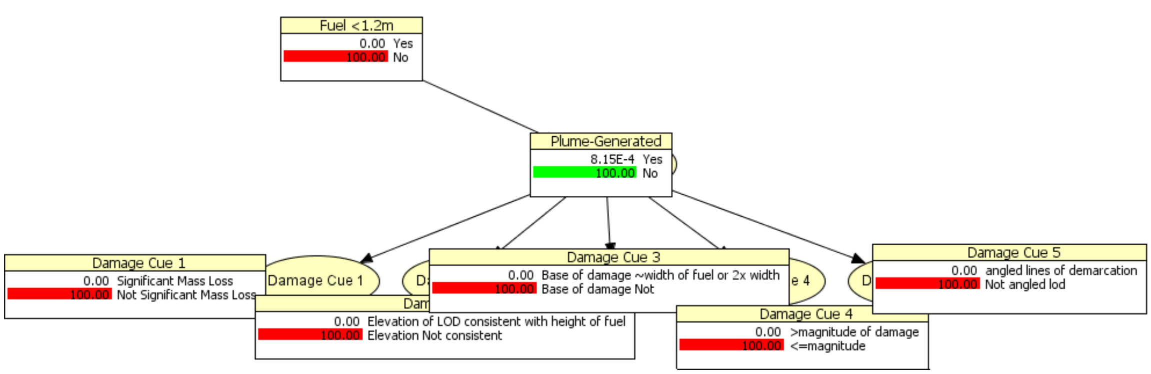


Figure F-2: FP1, 1500kW, 120 seconds, Fire Pattern 1, Plume Generated BN

Fire Pattern 1 – Upper Layer Generated:

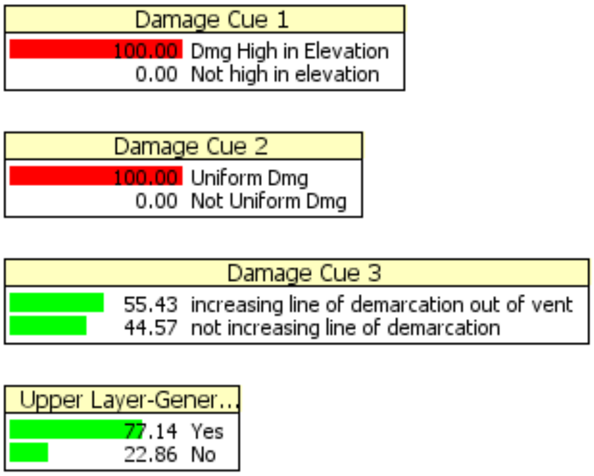


Figure F-3: FP1, 1500kW, 120 seconds, Fire Pattern 1, Upper Layer Generated Probabilities

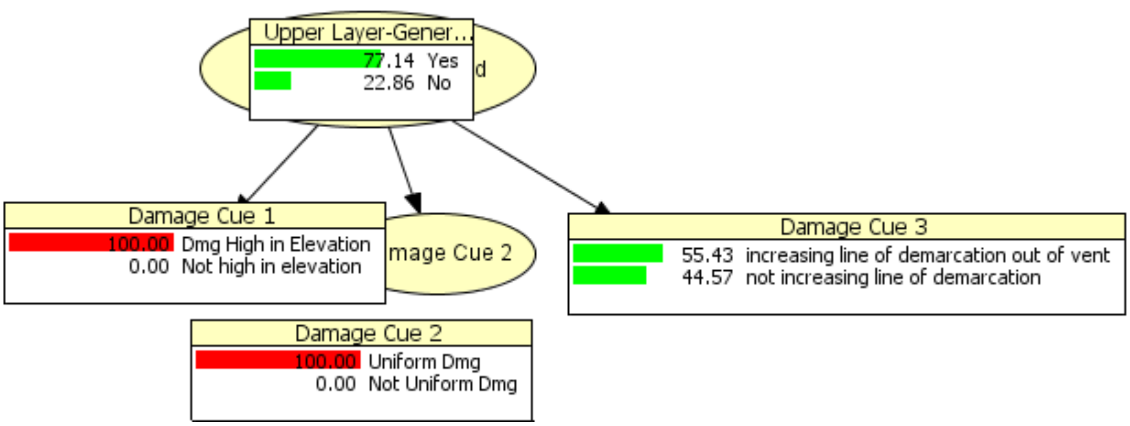


Figure F-4: FP1, 1500kW, 120 seconds, Fire Pattern 1, Upper Layer Generated BN

Fire Pattern 1 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 2 – Plume Generated:

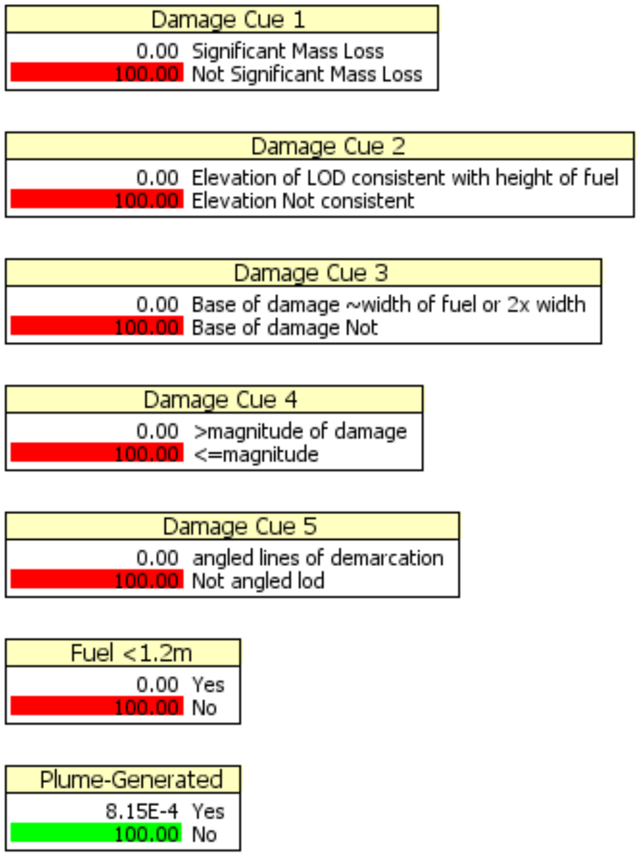


Figure F-5: FP1, 1500kW, 120 seconds, Fire Pattern 2, Plume Generated Probabilities

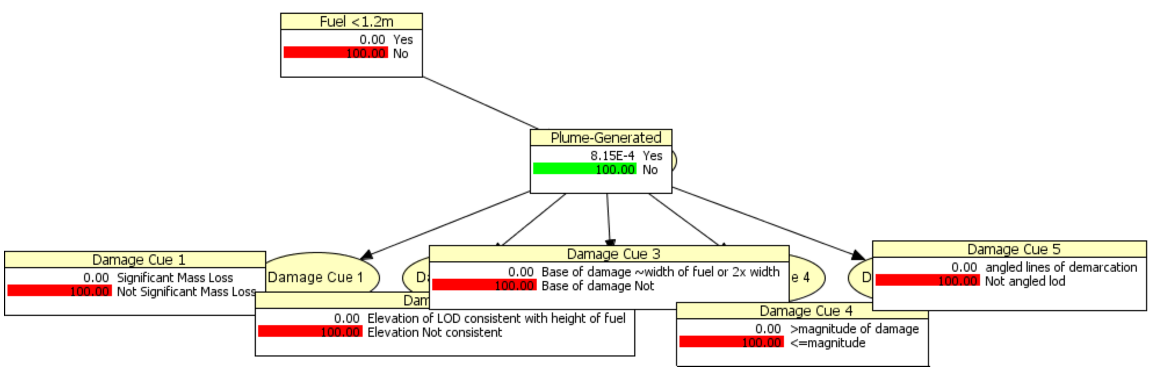


Figure F-6: FP1, 1500kW, 120 seconds, Fire Pattern 2, Plume Generated BN

Fire Pattern 2 – Upper Layer Generated:

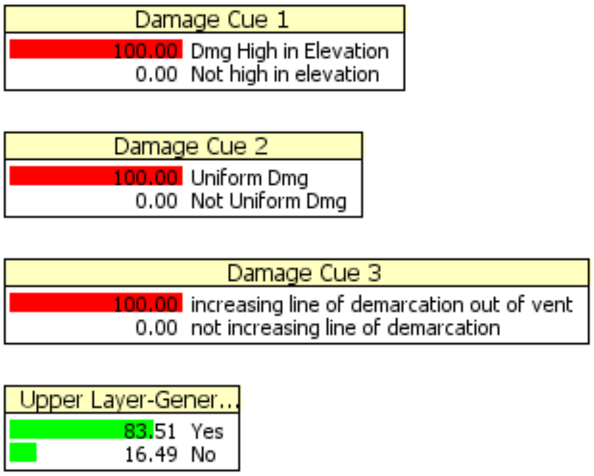


Figure F-7: FP1, 1500kW, 120 seconds, Fire Pattern 2, Upper Layer Generated Probabilities

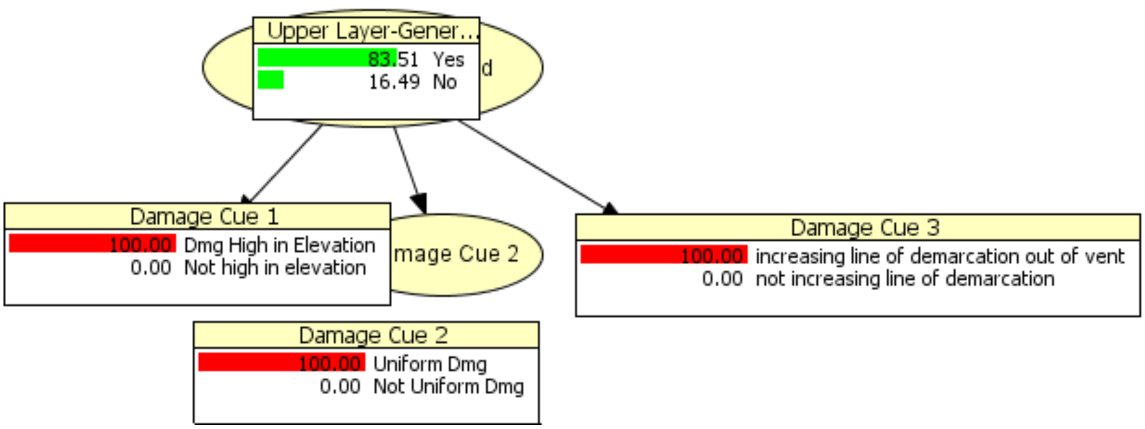


Figure F-8: FP1, 1500kW, 120 seconds, Fire Pattern 2, Upper Layer Generated BN

Fire Pattern 2 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 3 – Plume Generated:

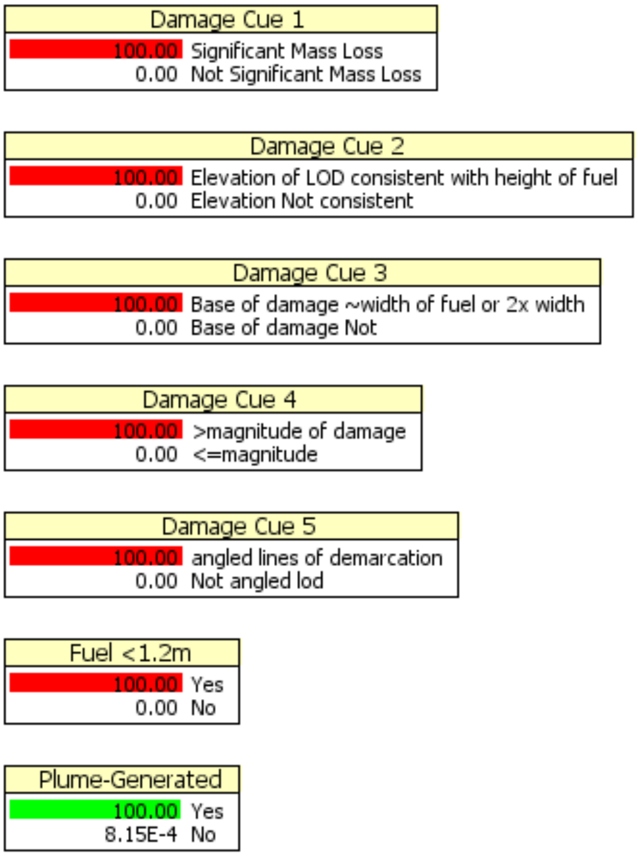


Figure F-9: FP1, 1500kW, 120 seconds, Fire Pattern 3, Plume Generated Probabilities

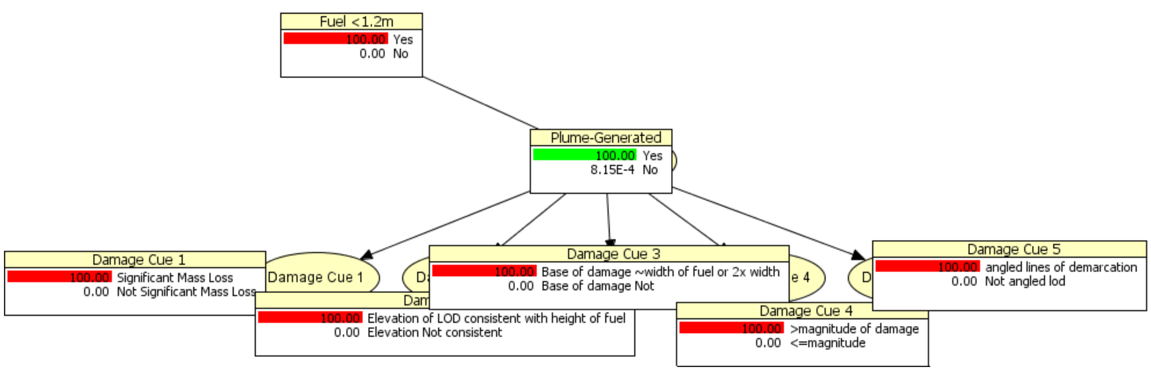


Figure F-10: FP1, 1500kW, 120 seconds, Fire Pattern 3, Plume Generated BN

Fire Pattern 3 – Upper Layer Generated:

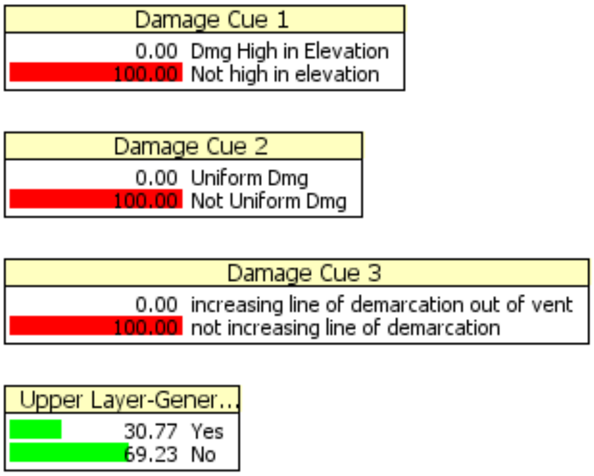


Figure F-11: FP1, 1500kW, 120 seconds, Fire Pattern 3, Upper Layer Generated Probabilities

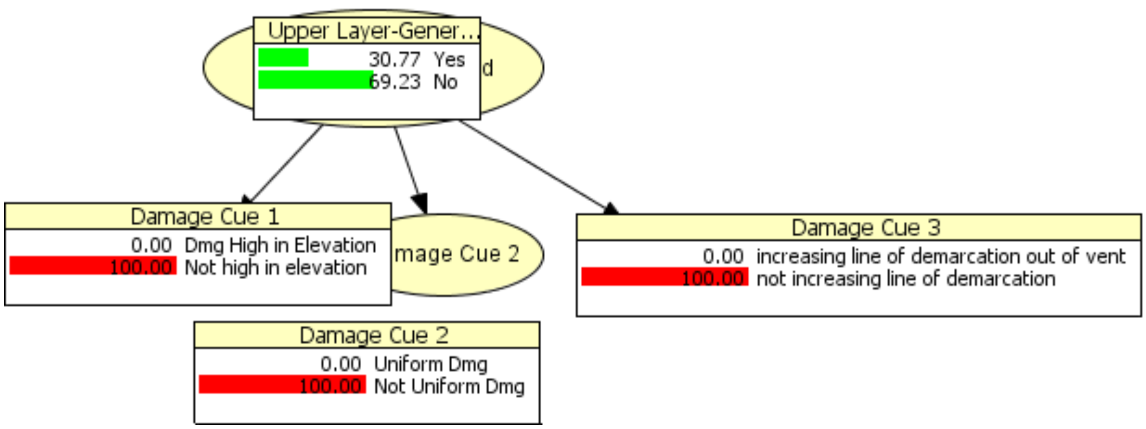


Figure F-12: FP1, 1500kW, 120 seconds, Fire Pattern 3, Upper Layer Generated BN

Fire Pattern 3 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 4 – Plume Generated:

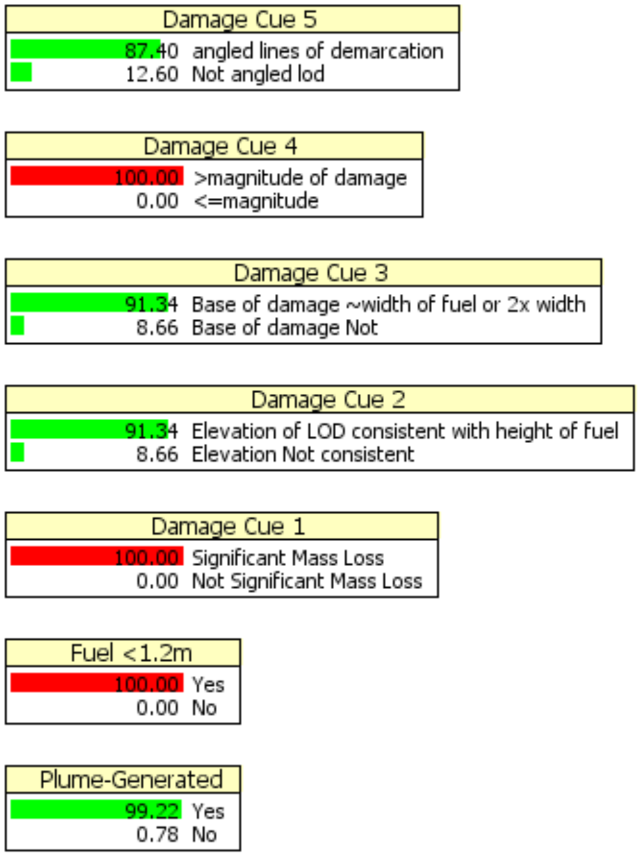


Figure F-13: FP1, 1500kW, 120 seconds, Fire Pattern 4, Plume Generated Probabilities

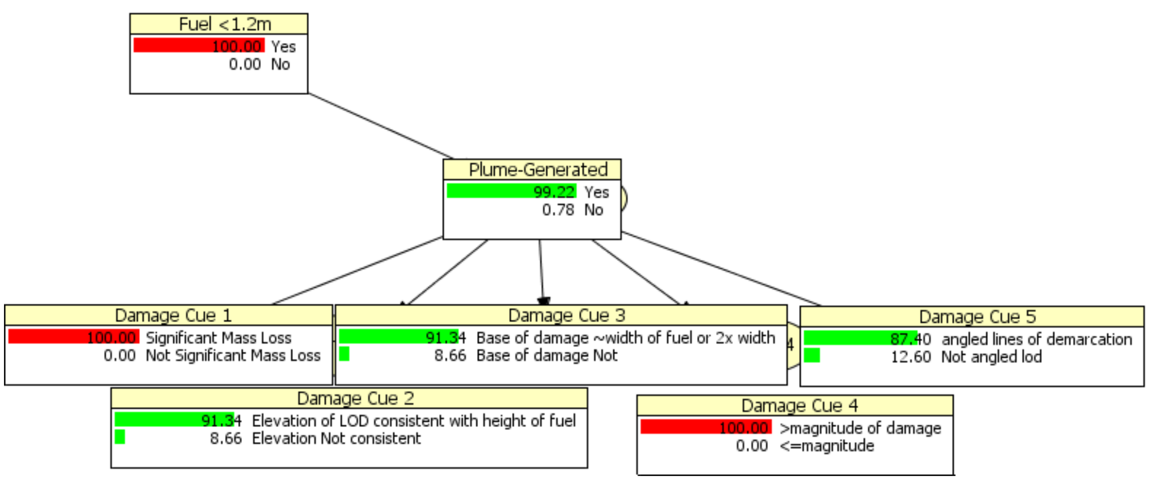


Figure F-14: FP1, 1500kW, 120 seconds, Fire Pattern 4, Plume Generated BN

Fire Pattern 4 – Upper Layer Generated:

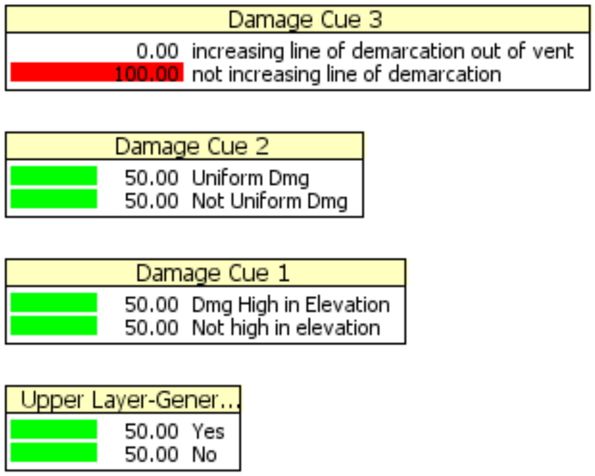


Figure F-15: FP1, 1500kW, 120 seconds, Fire Pattern 4, Upper Layer Generated Probabilities

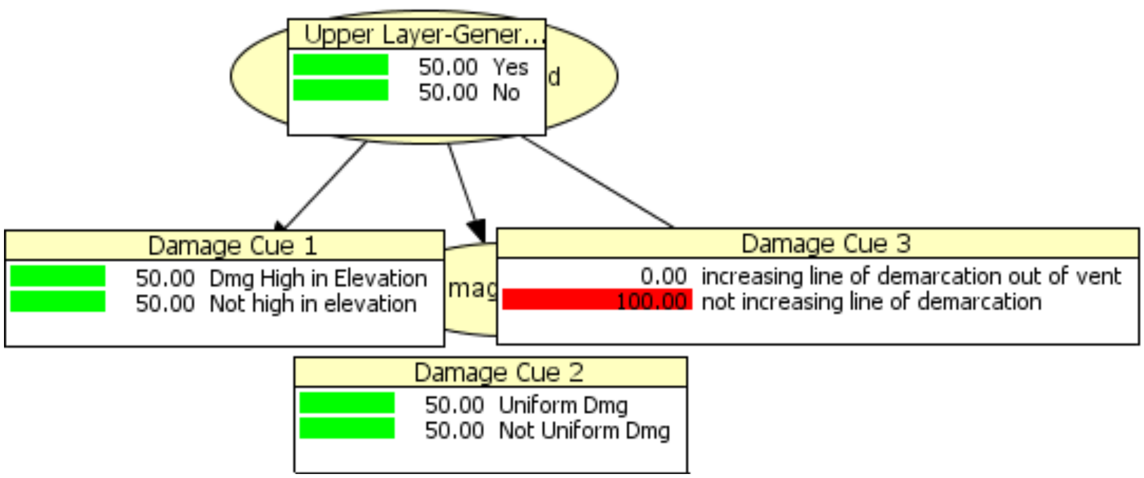


Figure F-16: FP1, 1500kW, 120 seconds, Fire Pattern 4, Upper Layer Generated BN

Fire Pattern 4 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Position 1, 1500 kW, 360 seconds

Fire Pattern 1 – Plume Generated:

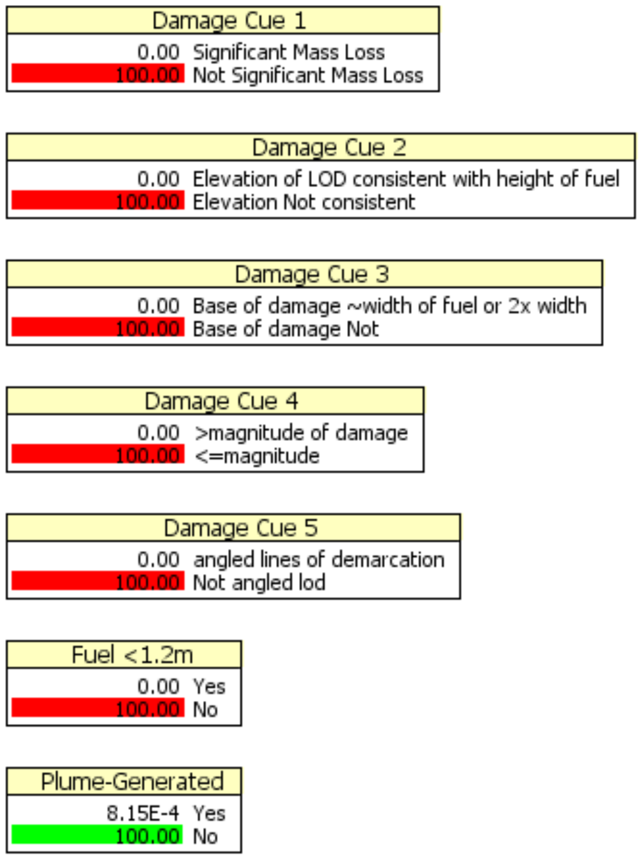


Figure F-17: FP1, 1500kW, 360 seconds, Fire Pattern 1, Plume Generated Probabilities

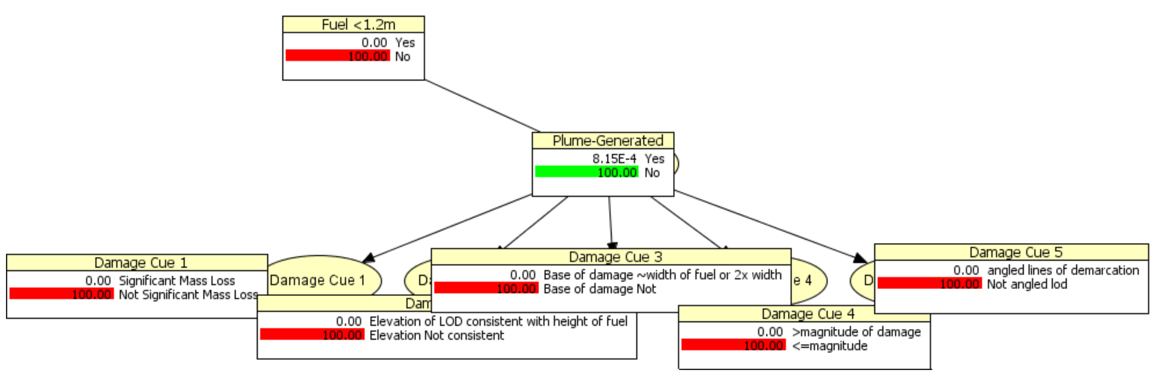


Figure F-18: FP1, 1500kW, 360 seconds, Fire Pattern 1, Plume Generated BN

Fire Pattern 1 – Upper Layer Generated:

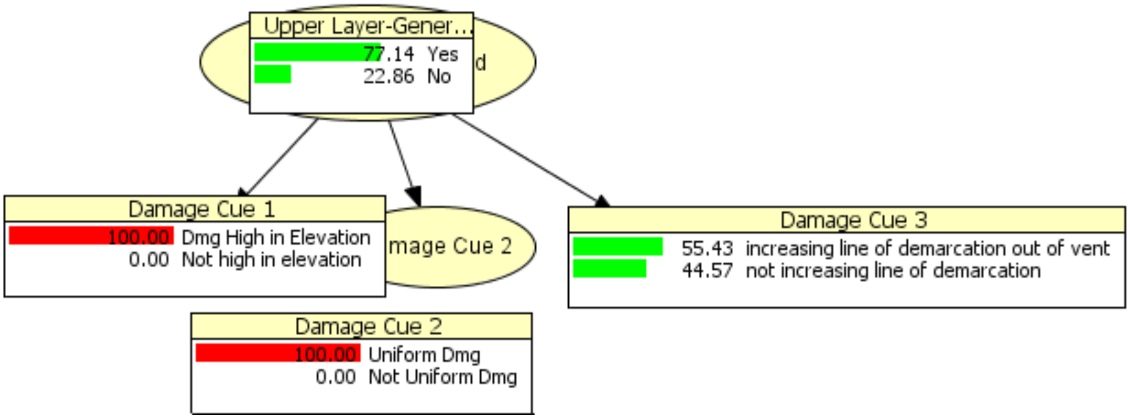


Figure F-19: FP1, 1500kW, 360 seconds, Fire Pattern 1, Upper Layer Generated BN

Fire Pattern 1 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 2 – Plume Generated:

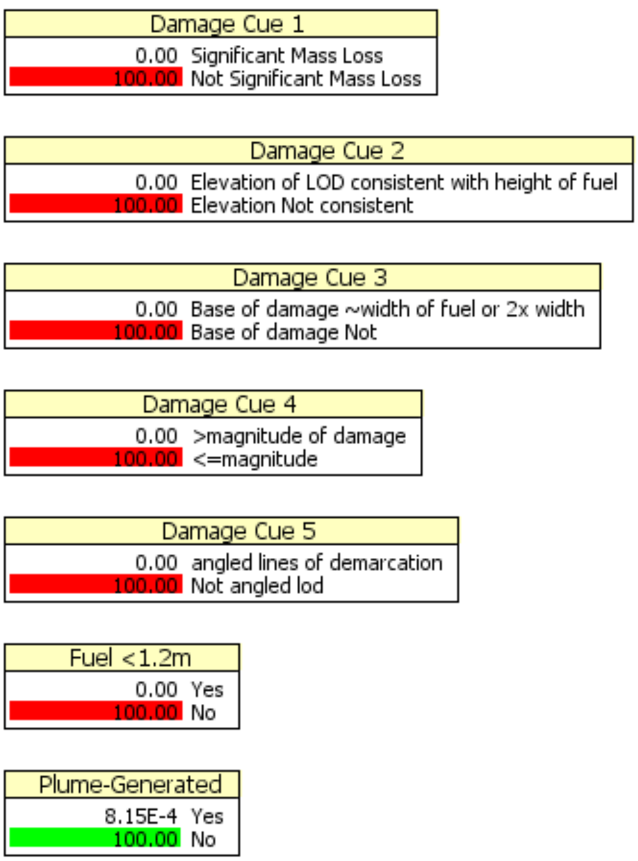


Figure F-20: FP1, 1500kW, 360 seconds, Fire Pattern 2, Plume Generated Probabilities

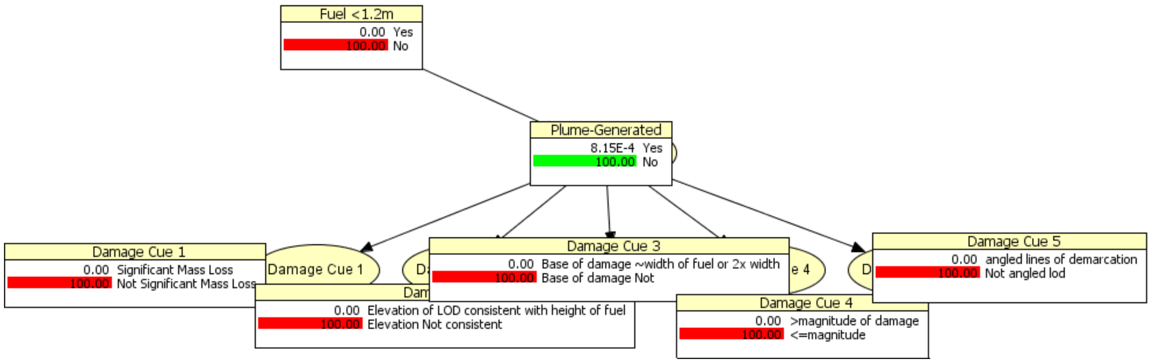


Figure F-21: FP1, 1500kW, 360 seconds, Fire Pattern 2, Plume Generated BN

Fire Pattern 2 – Upper Layer Generated:

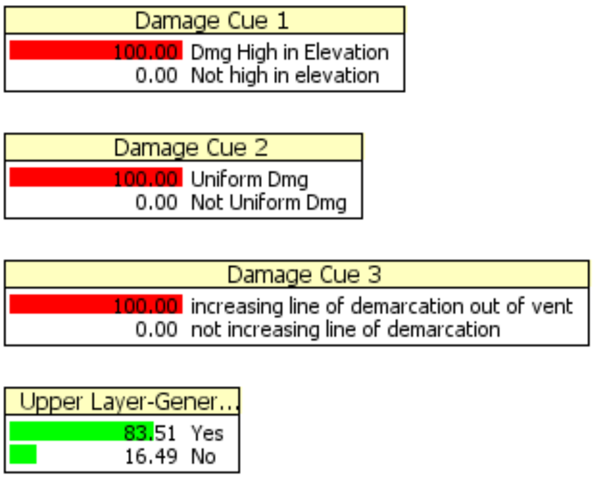


Figure F-22: FP1, 1500kW, 360 seconds, Fire Pattern 2, Upper Layer Generated Probabilities

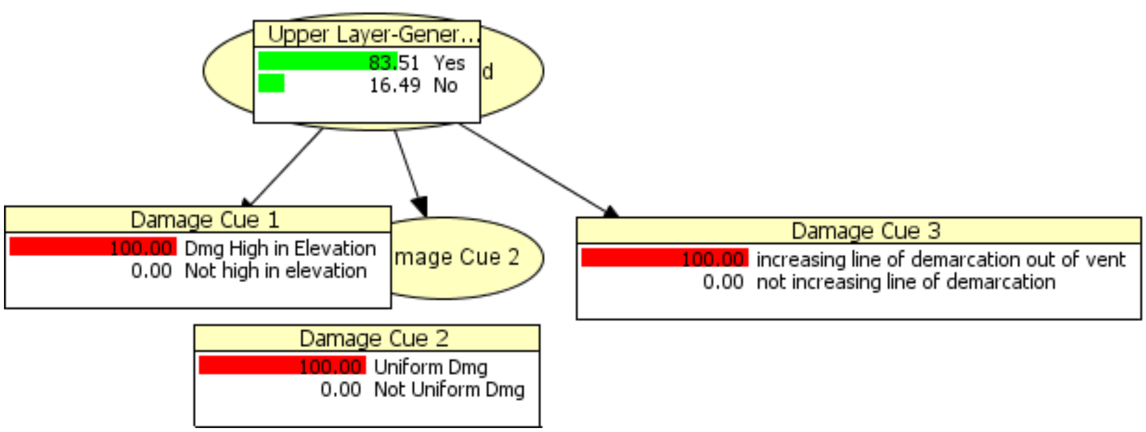


Figure F-23: FP1, 1500kW, 360 seconds, Fire Pattern 2, Upper Layer Generated BN

Fire Pattern 2 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 3 – Plume Generated:

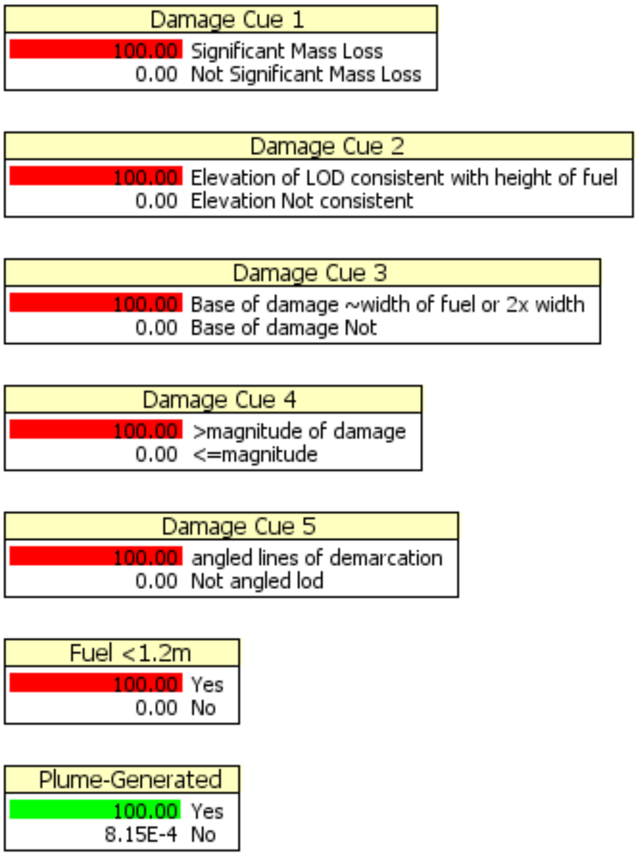


Figure F-24: FP1, 1500kW, 360 seconds, Fire Pattern 3, Plume Generated Probabilities

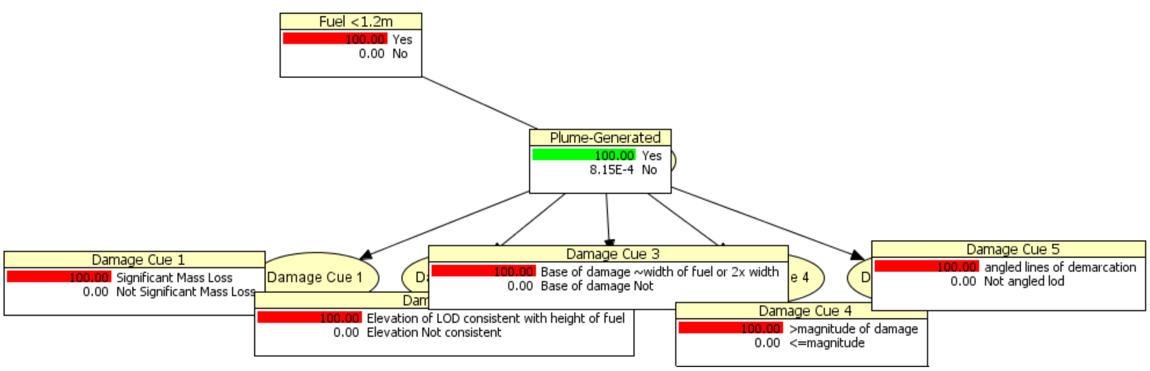


Figure F-25: FP1, 1500kW, 360 seconds, Fire Pattern 3, Plume Generated BN

Fire Pattern 3 – Upper Layer Generated:

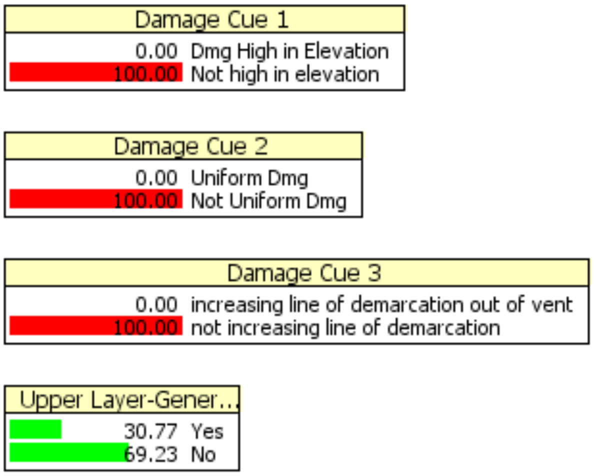


Figure F-26: FP1, 1500kW, 360 seconds, Fire Pattern 3, Upper Layer Generated Probabilities

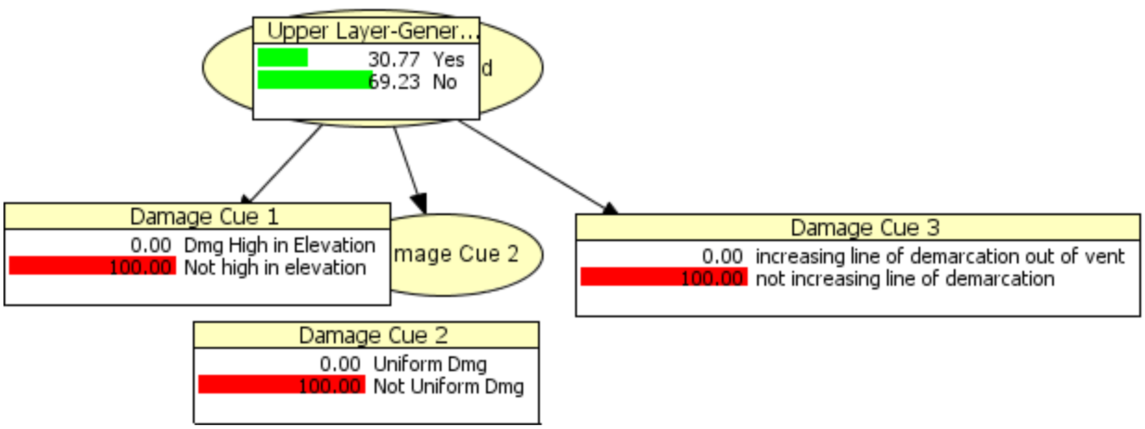


Figure F-27: FP1, 1500kW, 360 seconds, Fire Pattern 3, Upper Layer Generated BN

Fire Pattern 3 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 4 – Plume Generated:

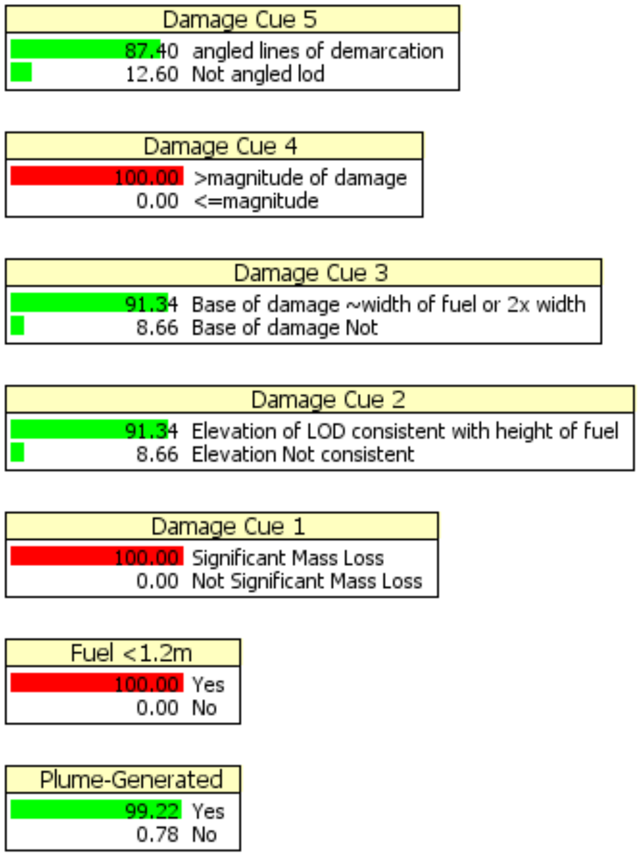


Figure F-28: FP1, 1500kW, 360 seconds, Fire Pattern 4, Plume Generated Probabilities

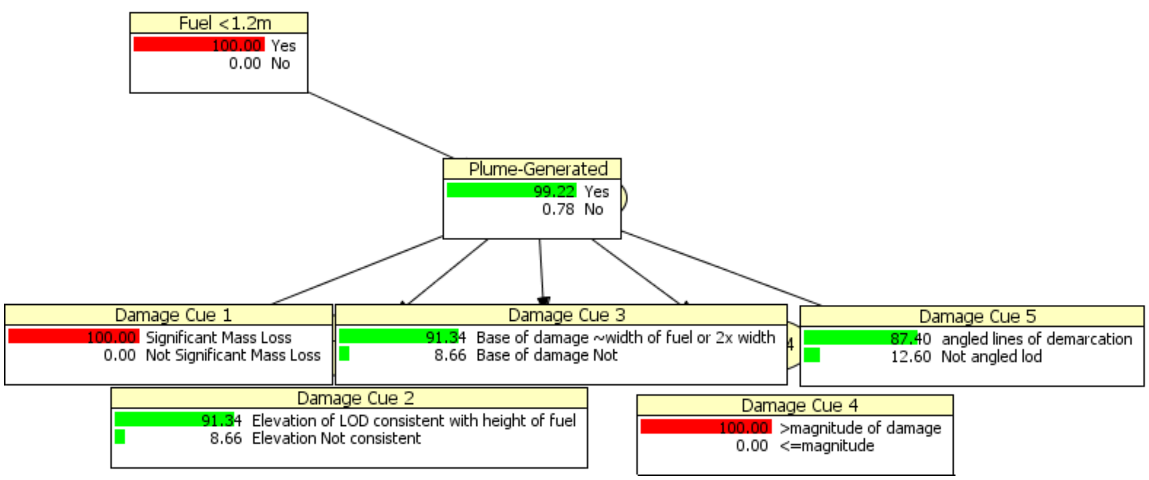


Figure F-29: FP1, 1500kW, 360 seconds, Fire Pattern 4, Plume Generated BN

Fire Pattern 4 – Upper Layer Generated:

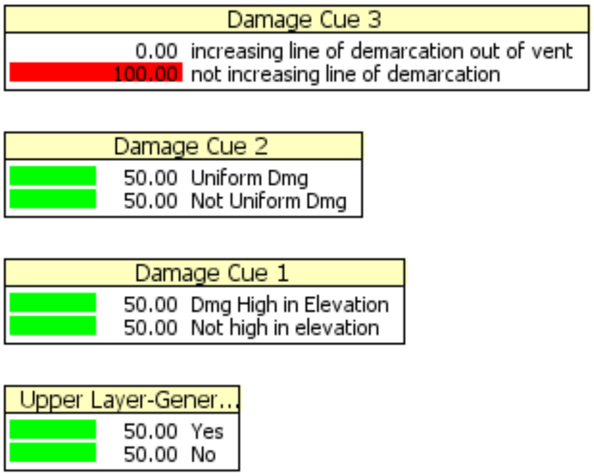


Figure F-30: FP1, 1500kW, 360 seconds, Fire Pattern 4, Upper Layer Generated Probabilities

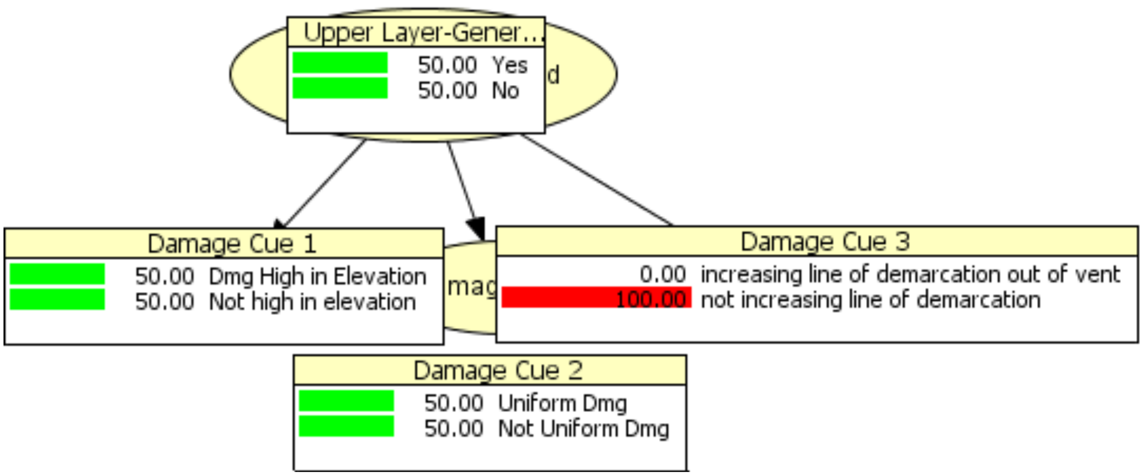


Figure F-31: FP1, 1500kW, 360 seconds, Fire Pattern 4, Upper Layer Generated BN

Fire Position 1, 1500 kW, 900 seconds

Fire Pattern 1 – Plume Generated:

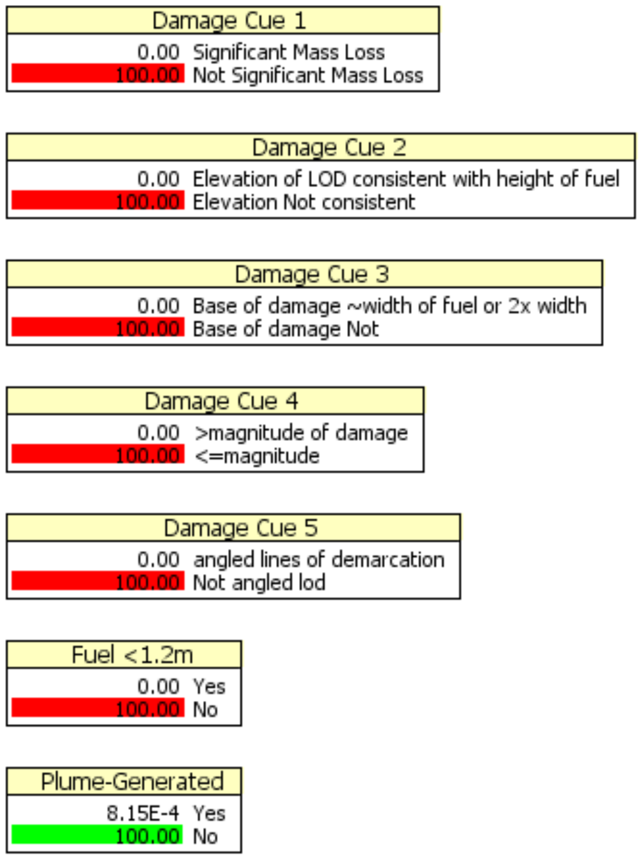


Figure F-32: FP1, 1500kW, 900 seconds, Fire Pattern 1, Plume Generated Probabilities

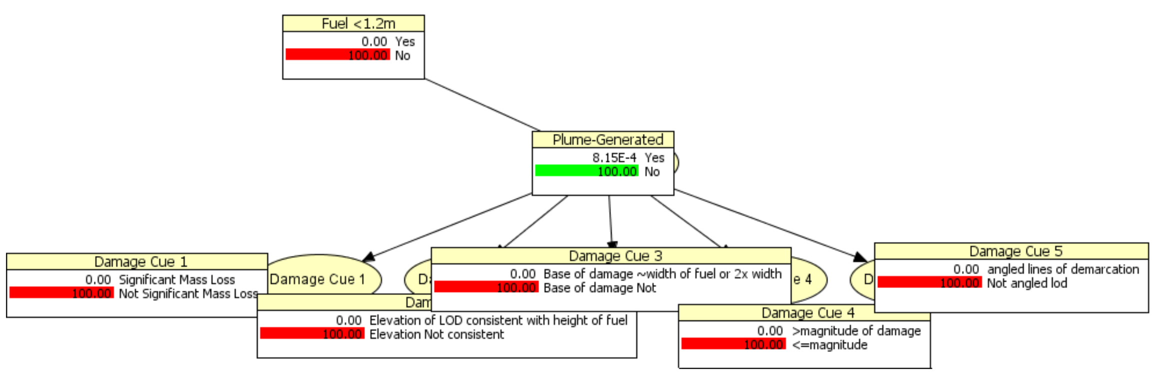


Figure F-33: FP1, 1500kW, 900 seconds, Fire Pattern 1, Plume Generated BN

Fire Pattern 1 – Upper Layer Generated:

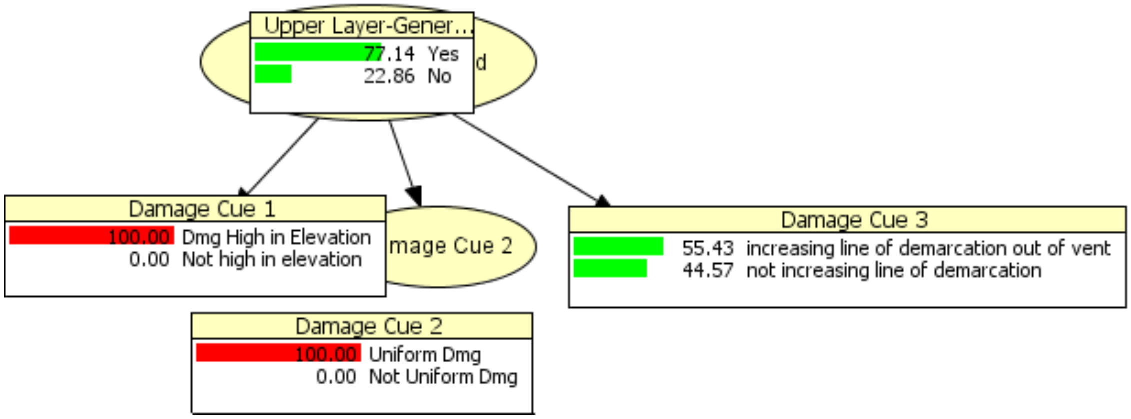


Figure F-34: FP1, 1500kW, 900 seconds, Fire Pattern 1, Upper Layer Generated BN

Fire Pattern 1 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 2 – Plume Generated:

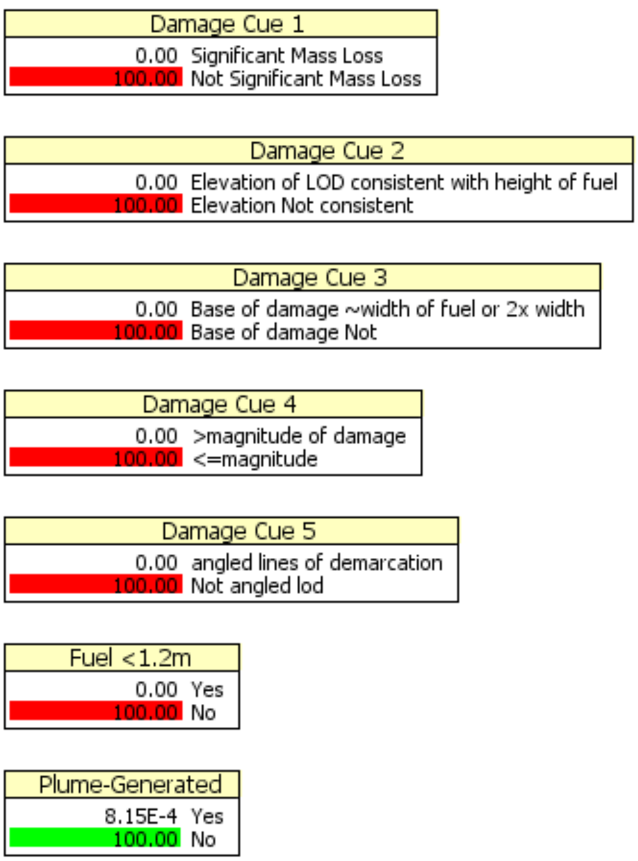


Figure F-35: FP1, 1500kW, 900 seconds, Fire Pattern 2, Plume Generated Probabilities

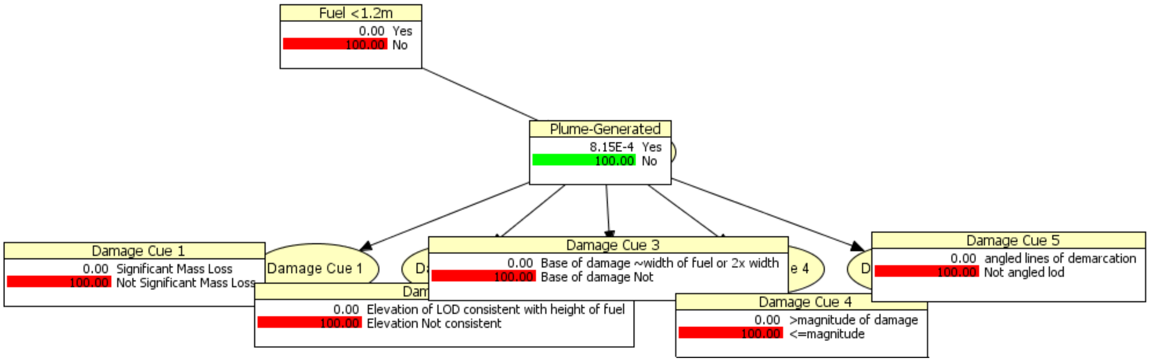


Figure F-36: FP1, 1500kW, 900 seconds, Fire Pattern 2, Plume Generated BN

Fire Pattern 2 – Upper Layer Generated:

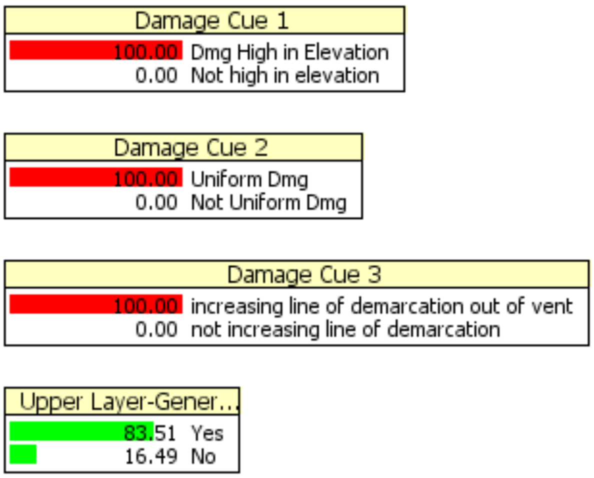


Figure F-37: FP1, 1500kW, 900 seconds, Fire Pattern 2, Upper Layer Generated Probabilities

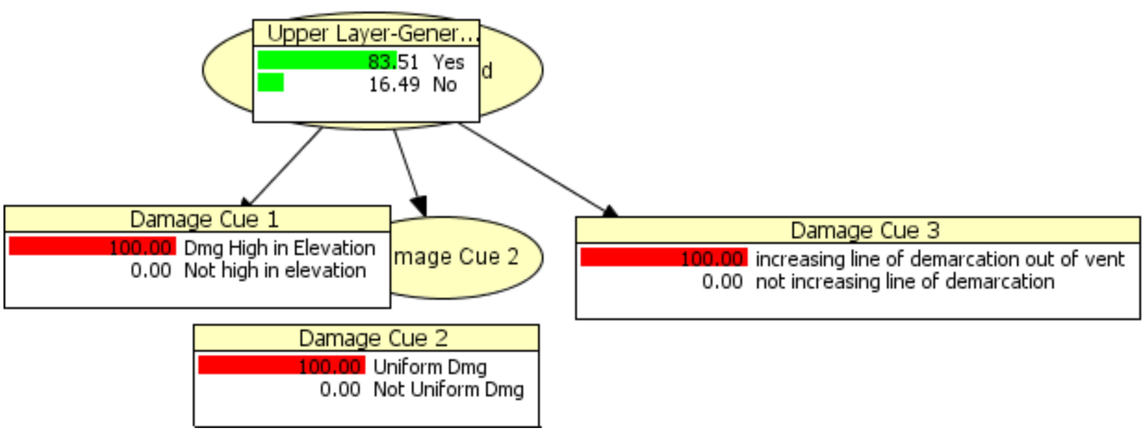


Figure F-38: FP1, 1500kW, 900 seconds, Fire Pattern 2, Upper Layer Generated BN

Fire Pattern 2 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 3 – Plume Generated:

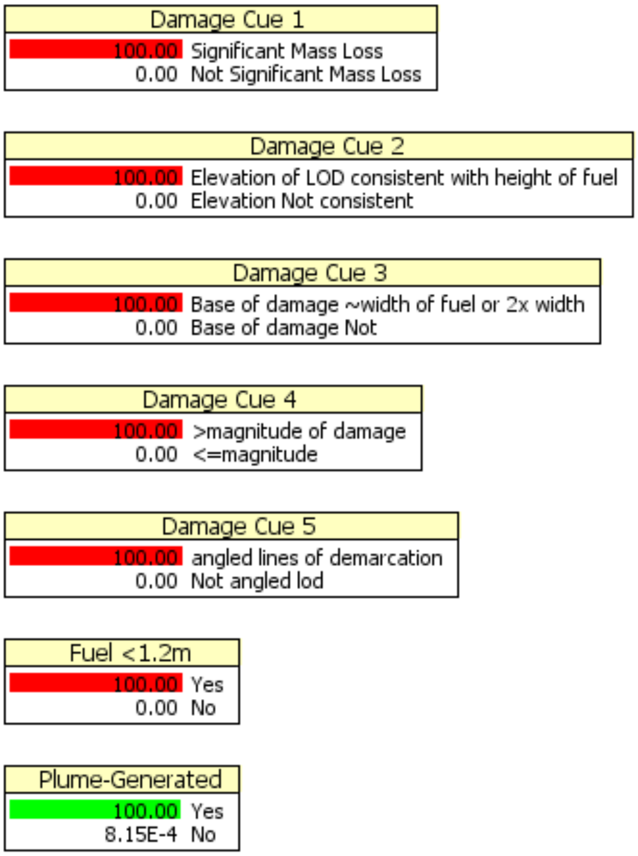


Figure F-39: FP1, 1500kW, 900 seconds, Fire Pattern 3, Plume Generated Probabilities

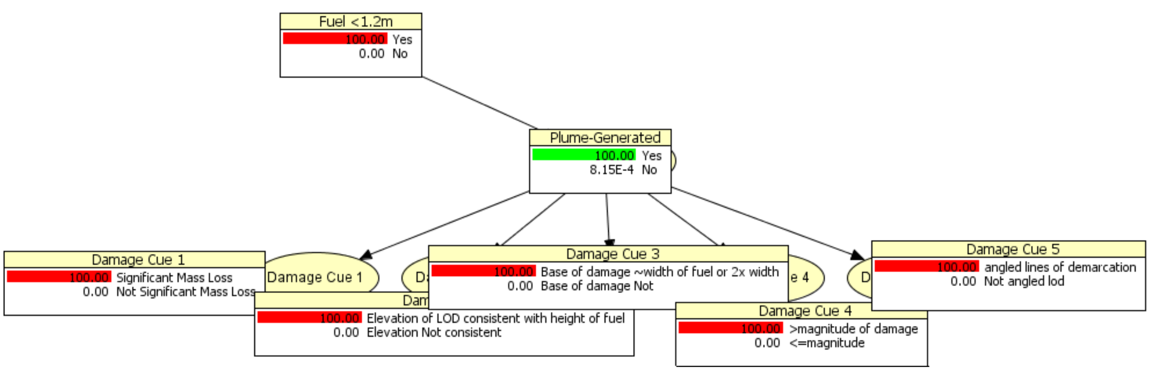


Figure F-40: FP1, 1500kW, 900 seconds, Fire Pattern 3, Plume Generated BN

Fire Pattern 3 – Upper Layer Generated:

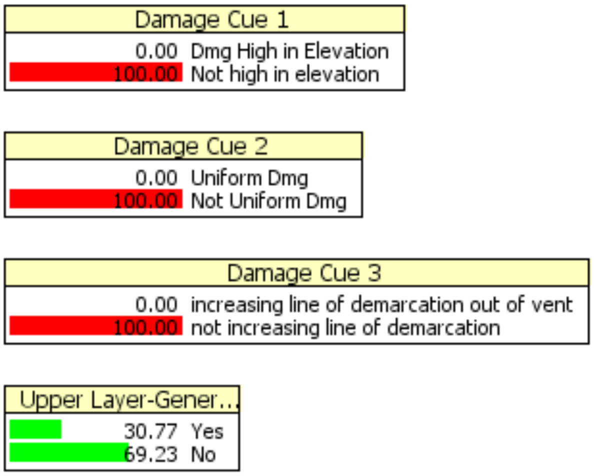


Figure F-41: FP1, 1500kW, 900 seconds, Fire Pattern 3, Upper Layer Generated Probabilities

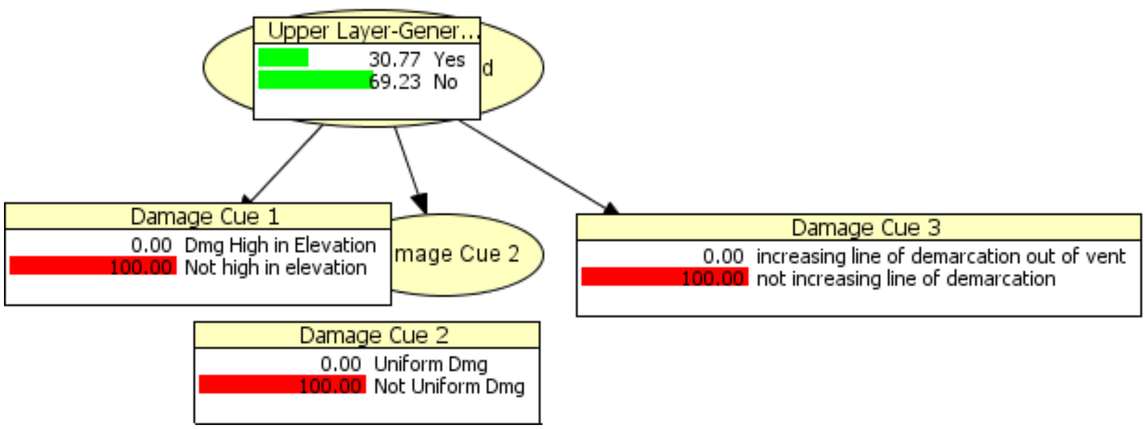


Figure F-42: FP1, 1500kW, 900 seconds, Fire Pattern 3, Upper Layer Generated BN

Fire Pattern 3 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 4 – Plume Generated:

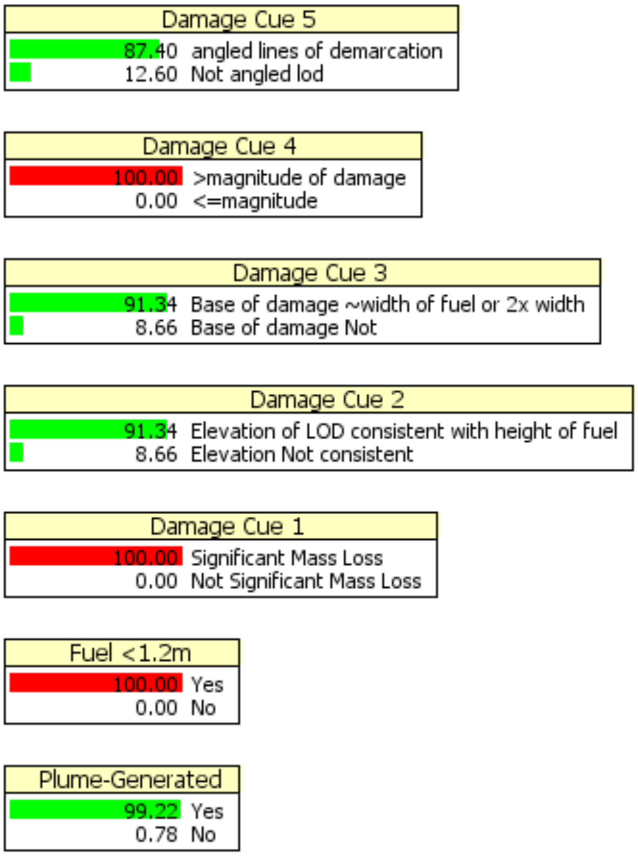


Figure F-43: FP1, 1500kW, 900 seconds, Fire Pattern 4, Plume Generated Probabilities

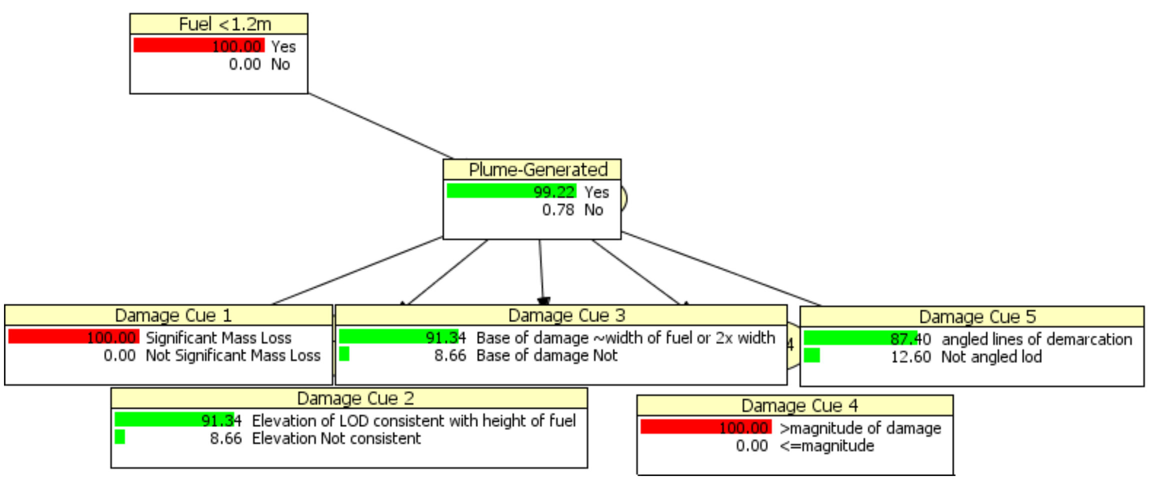


Figure F-44: FP1, 1500kW, 900 seconds, Fire Pattern 4, Plume Generated BN

Fire Pattern 4 – Upper Layer Generated:

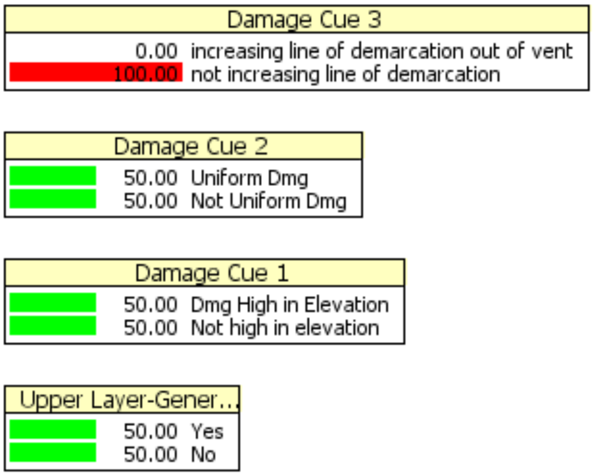


Figure F-45: FP1, 1500kW, 900 seconds, Fire Pattern 4, Upper Layer Generated Probabilities

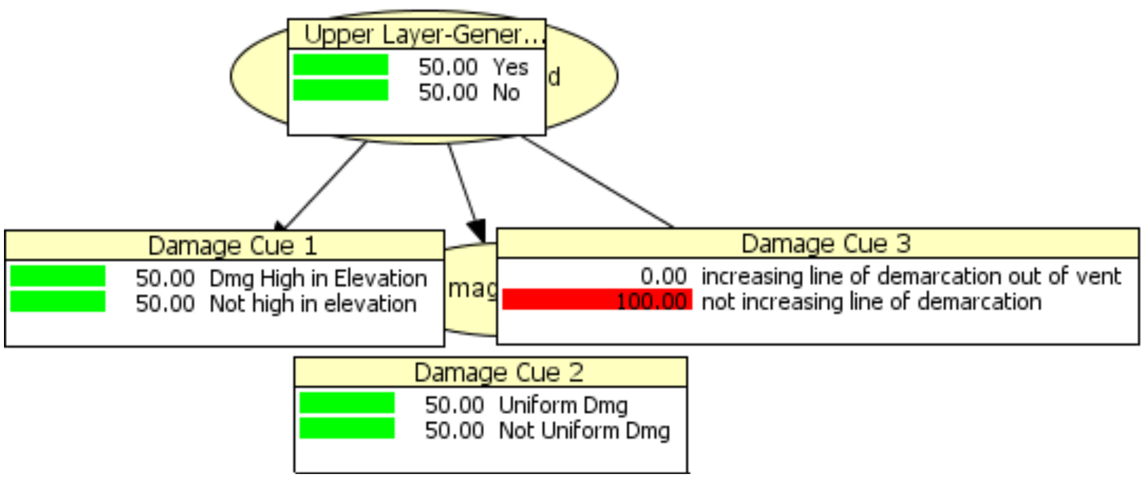


Figure F-46: FP1, 1500kW, 900 seconds, Fire Pattern 4, Upper Layer Generated BN

Fire Position 1, 4000 kW, 120 seconds

Fire Pattern 1 – Plume Generated:

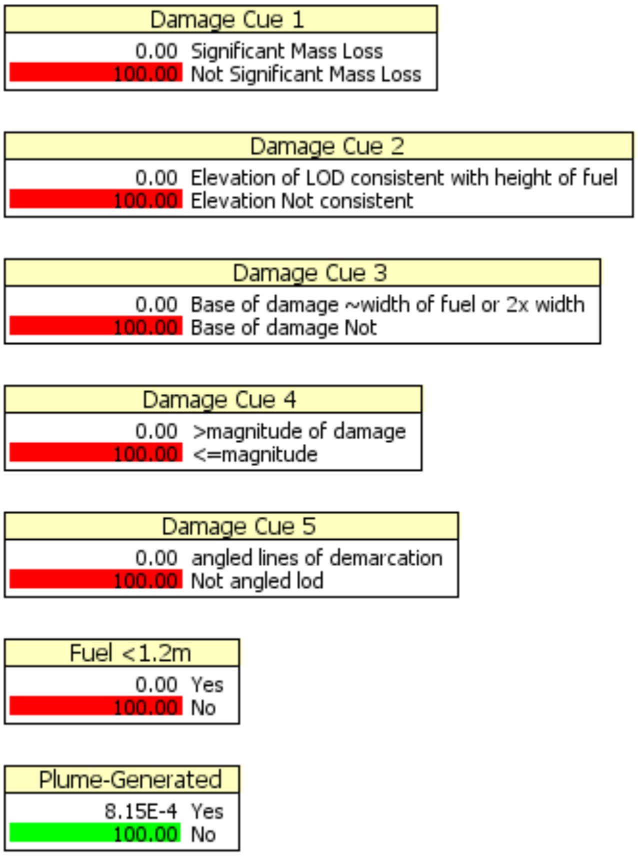


Figure F-47: FP1, 4000kW, 120 seconds, Fire Pattern 1, Plume Generated Probabilities

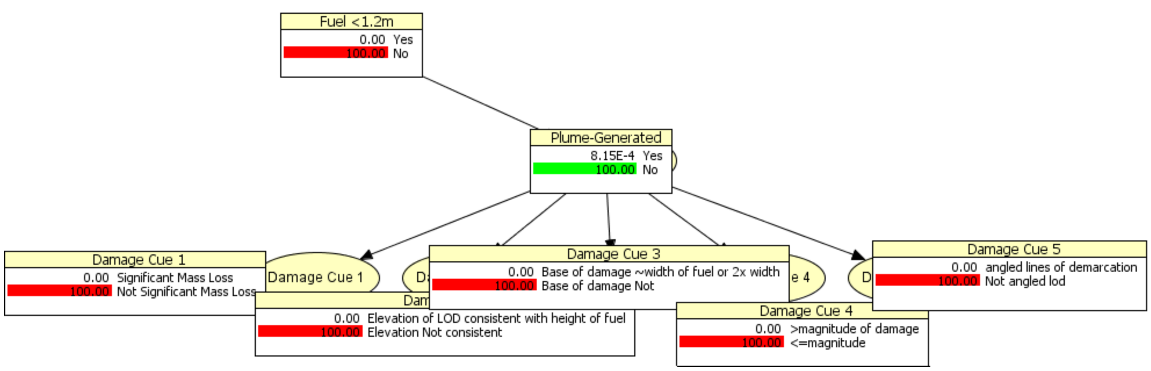


Figure F-48: FP1, 4000kW, 120 seconds, Fire Pattern 1, Plume Generated BN

Fire Pattern 1 – Upper Layer Generated:

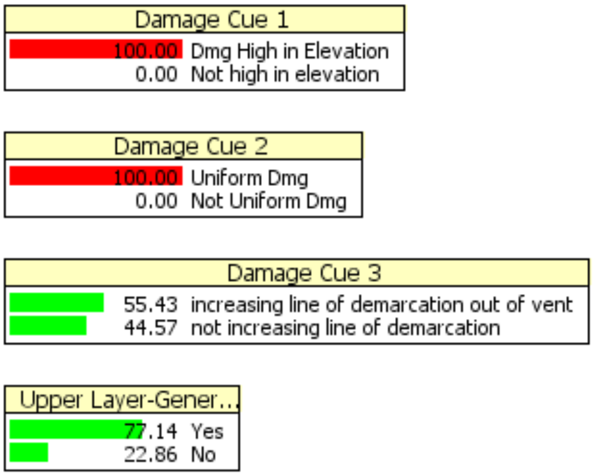


Figure F-49: FP1, 4000kW, 120 seconds, Fire Pattern 1, Upper Layer Generated Probabilities

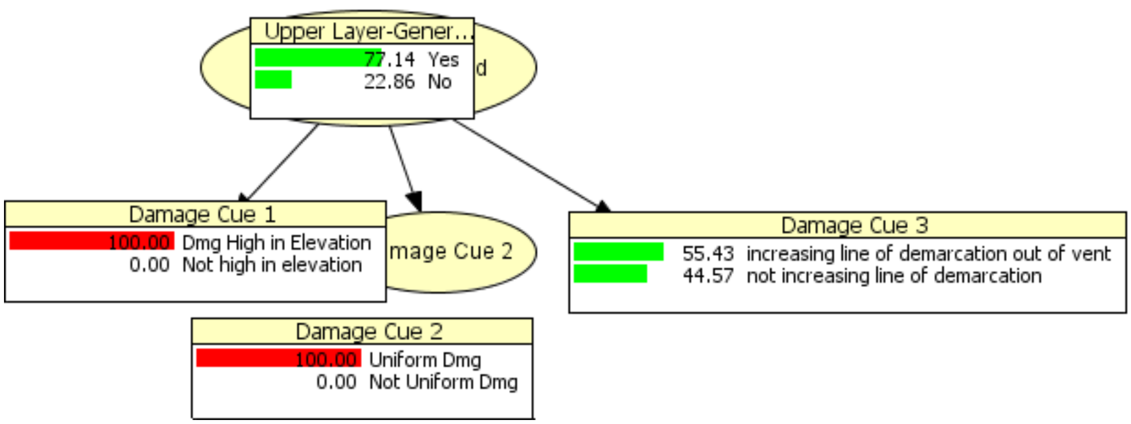


Figure F-50: FP1, 4000kW, 120 seconds, Fire Pattern 1, Upper Layer Generated BN

Fire Pattern 1 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 2 – Plume Generated:

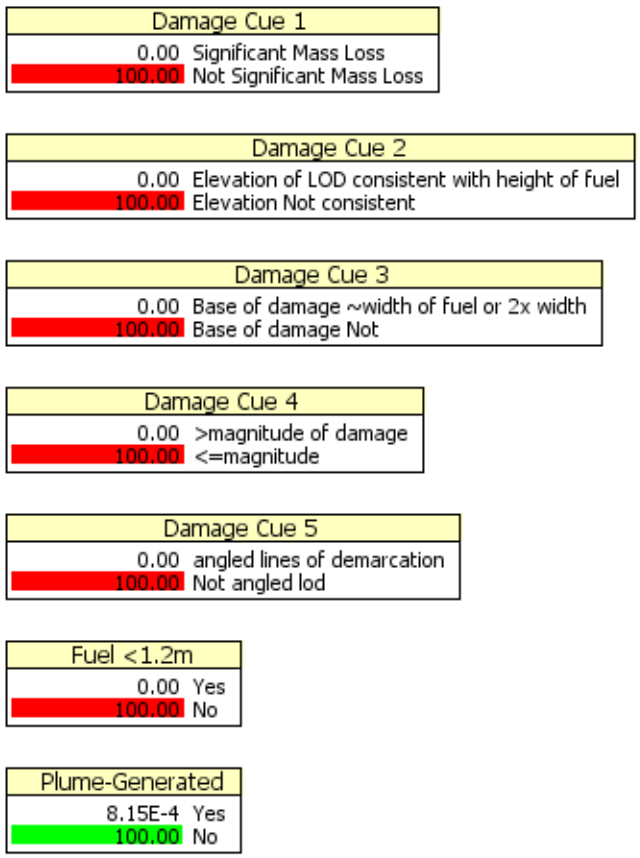


Figure F-51: FP1, 4000kW, 120 seconds, Fire Pattern 2, Plume Generated Probabilities

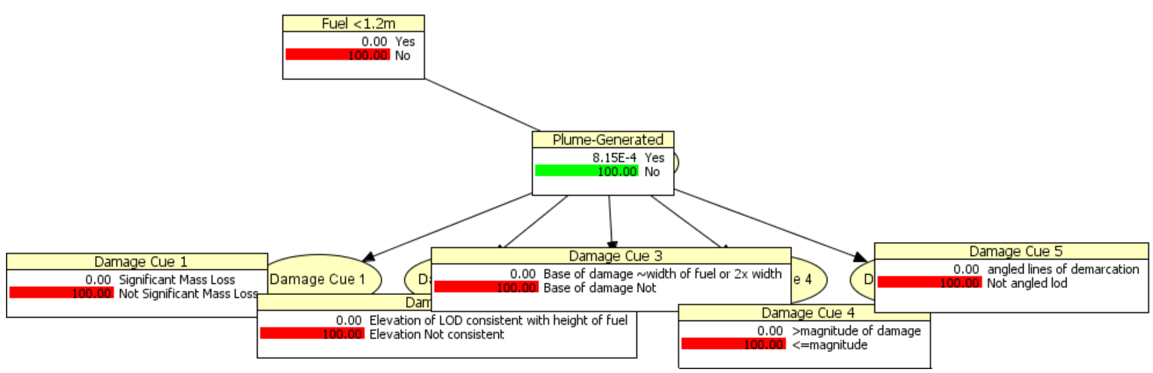


Figure F-52: FP1, 4000kW, 120 seconds, Fire Pattern 2, Plume Generated BN

Fire Pattern 2 – Upper Layer Generated:

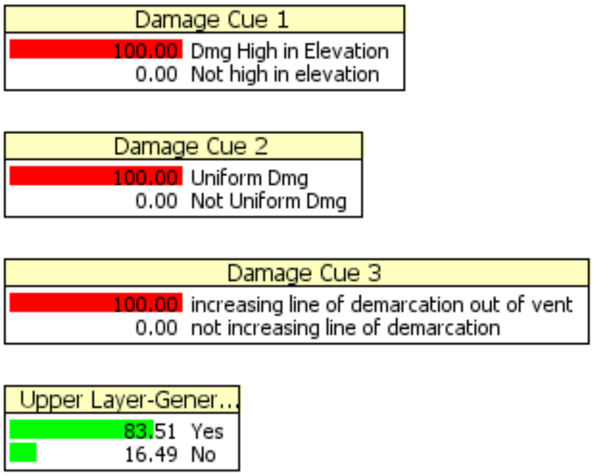


Figure F-53: FP1, 4000kW, 120 seconds, Fire Pattern 2, Upper Layer Generated Probabilities

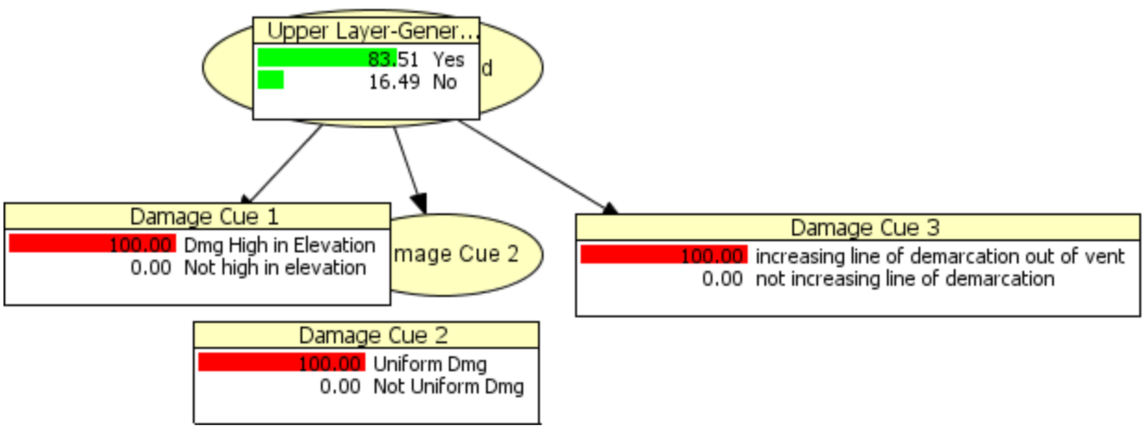


Figure F-54: FP1, 4000kW, 120 seconds, Fire Pattern 2, Upper Layer Generated BN

Fire Pattern 2 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 3 – Plume Generated:

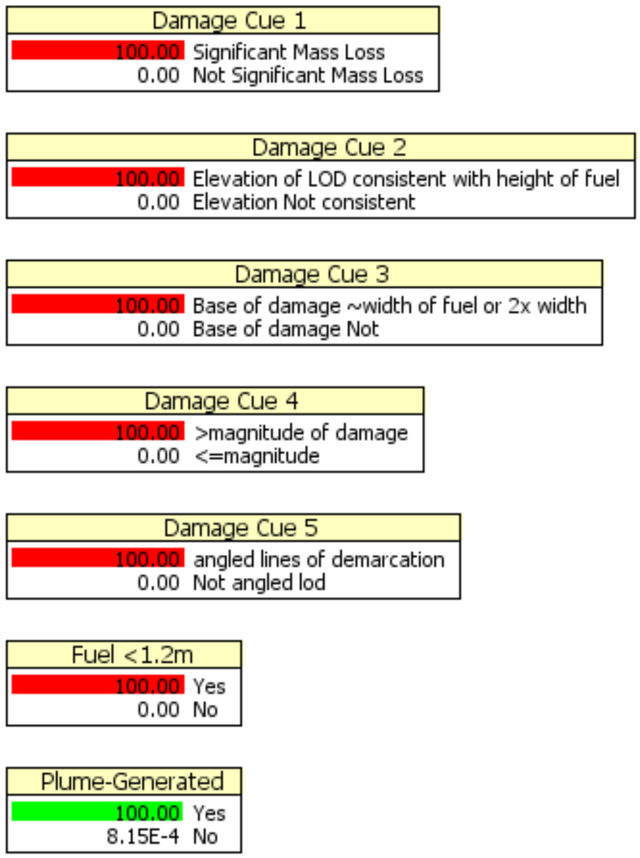


Figure F-55: FP1, 4000kW, 120 seconds, Fire Pattern 3, Plume Generated Probabilities

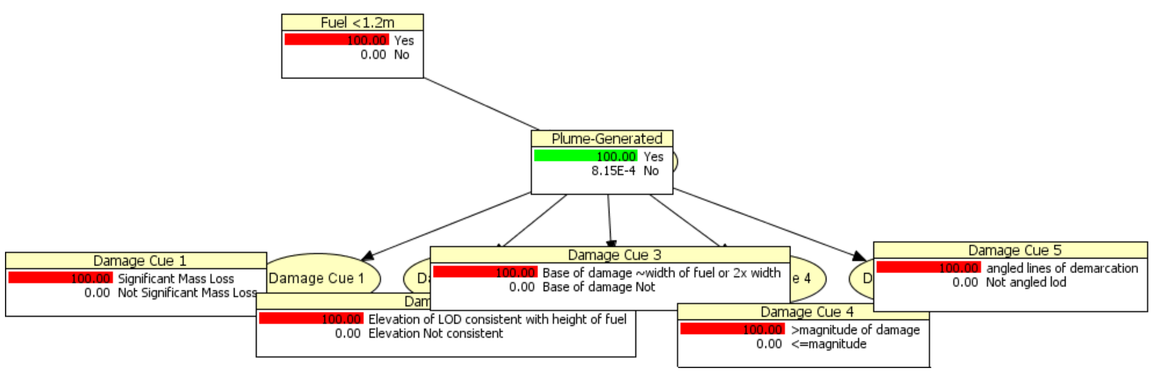


Figure F-56: FP1, 4000kW, 120 seconds, Fire Pattern 3, Plume Generated BN

Fire Pattern 3 – Upper Layer Generated:

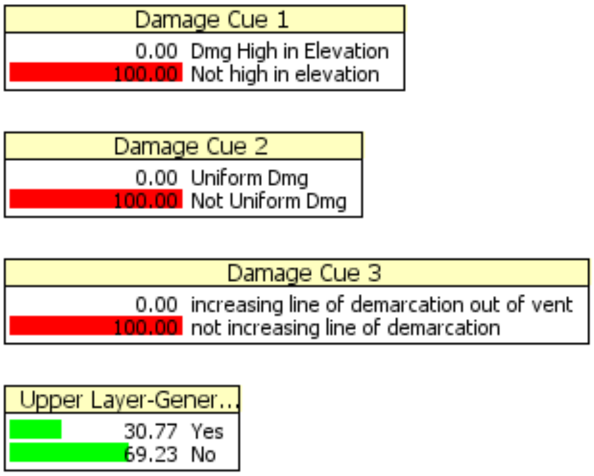


Figure F-57: FP1, 4000kW, 120 seconds, Fire Pattern 3, Upper Layer Generated Probabilities

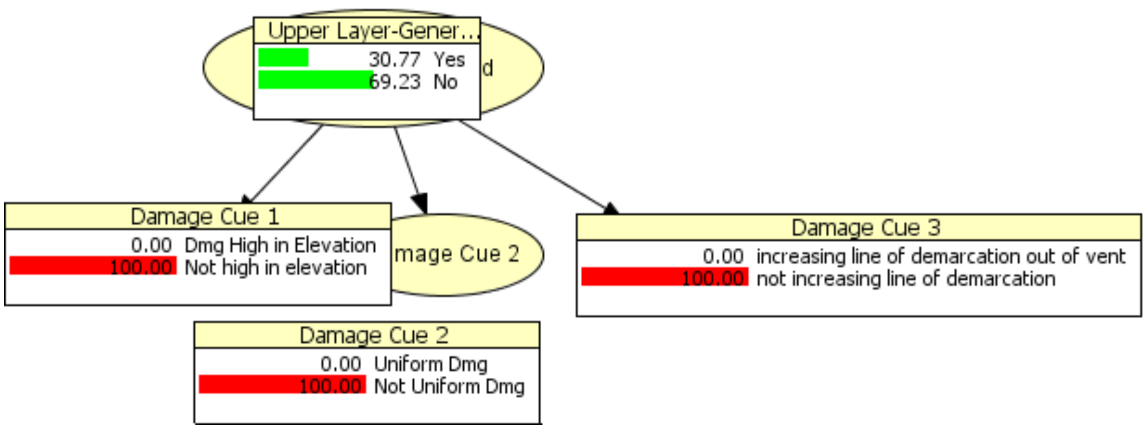


Figure F-58: FP1, 4000kW, 120 seconds, Fire Pattern 3, Upper Layer Generated BN

Fire Pattern 3 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Pattern 4 – Plume Generated:

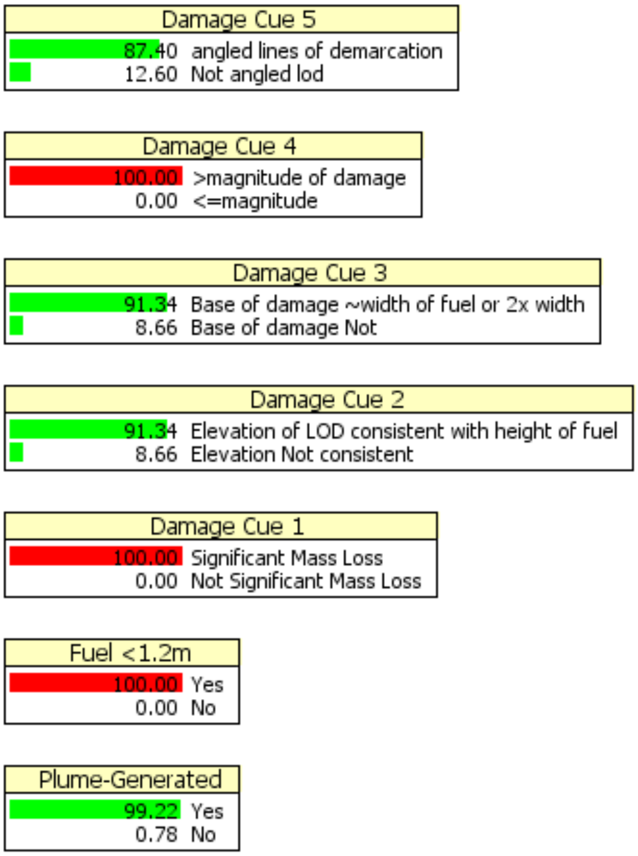


Figure F-59: FP1, 4000kW, 120 seconds, Fire Pattern 4, Plume Generated Probabilities

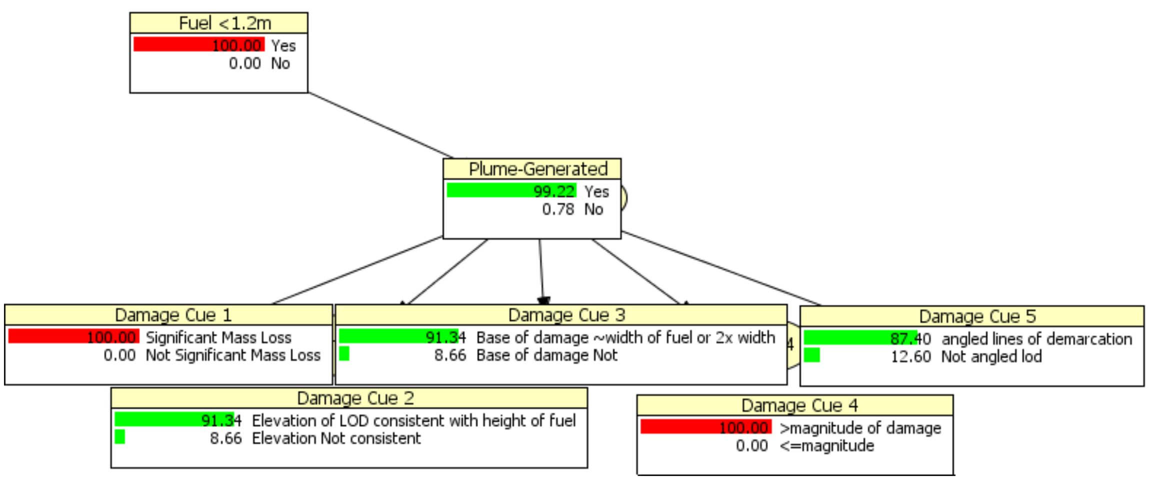


Figure F-60: FP1, 4000kW, 120 seconds, Fire Pattern 4, Plume Generated BN

Fire Pattern 4 – Upper Layer Generated:

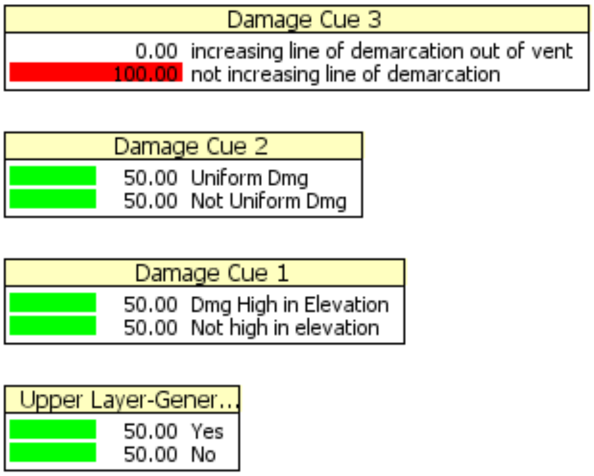


Figure F-61: FP1, 4000kW, 120 seconds, Fire Pattern 4, Upper Layer Generated Probabilities

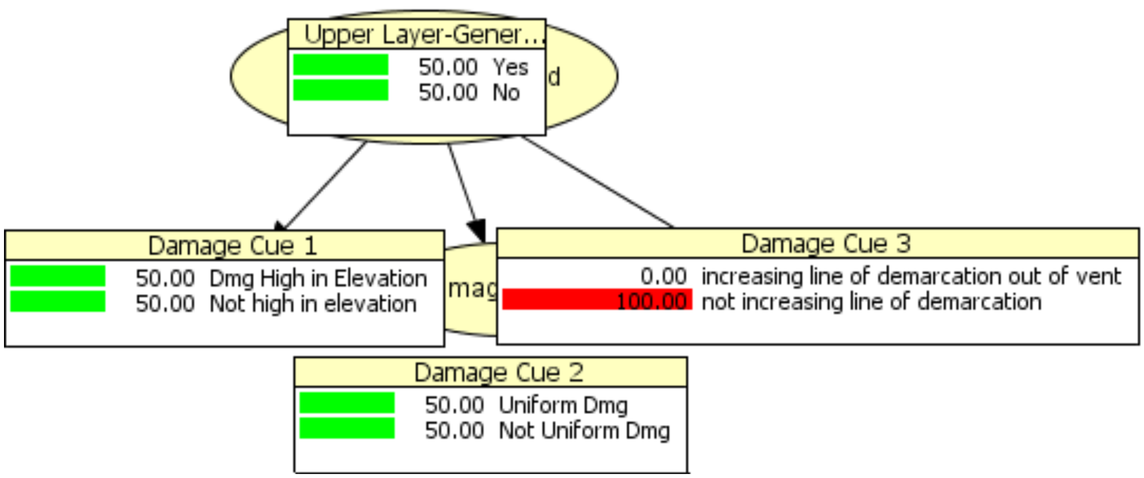


Figure F-62: FP1, 4000kW, 120 seconds, Fire Pattern 4, Upper Layer Generated BN

Fire Pattern 4 – Ventilation-Generated:

Not applicable as the fire did not transition to ventilation-controlled conditions

Fire Position 1, 4000 kW, 360 seconds

Fire Pattern 1 – Plume Generated:

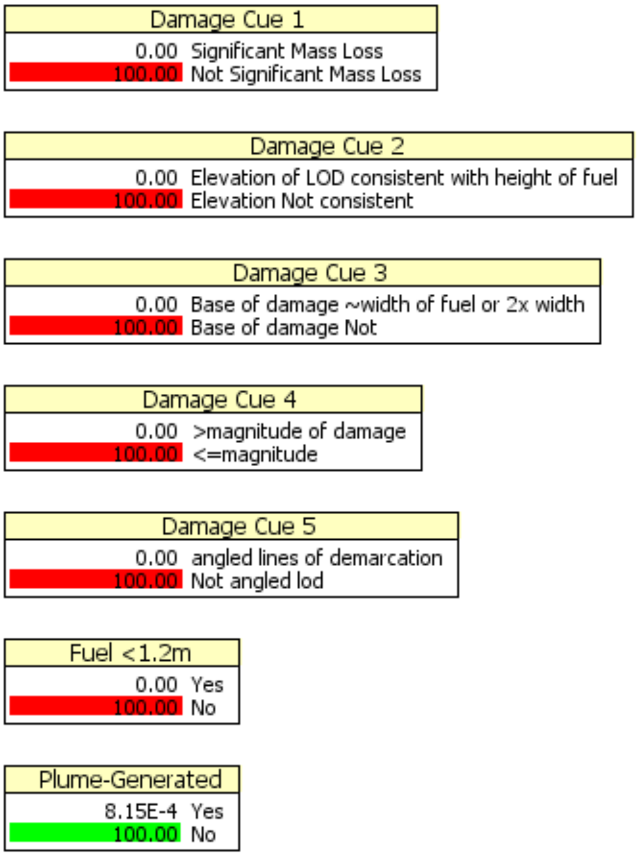


Figure F-63: FP1, 4000kW, 360 seconds, Fire Pattern 1, Plume Generated Probabilities

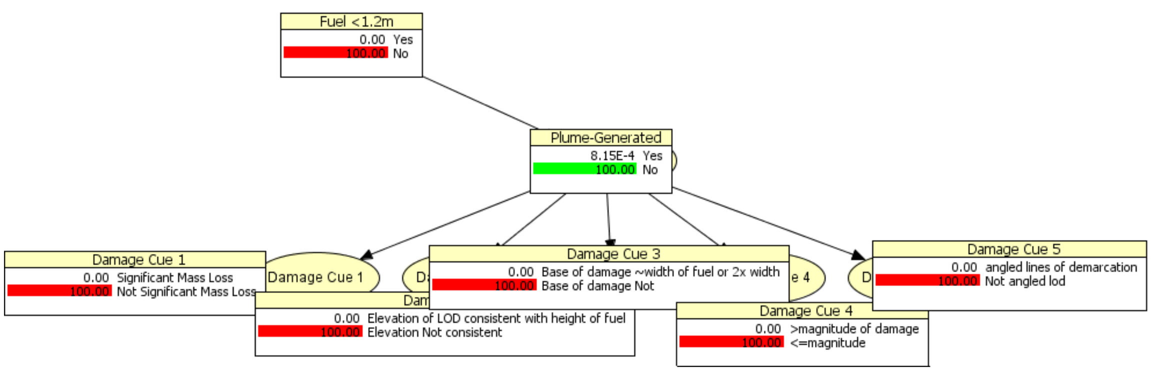


Figure F-64: FP1, 4000kW, 360 seconds, Fire Pattern 1, Plume Generated BN

Fire Pattern 1 – Upper Layer Generated:

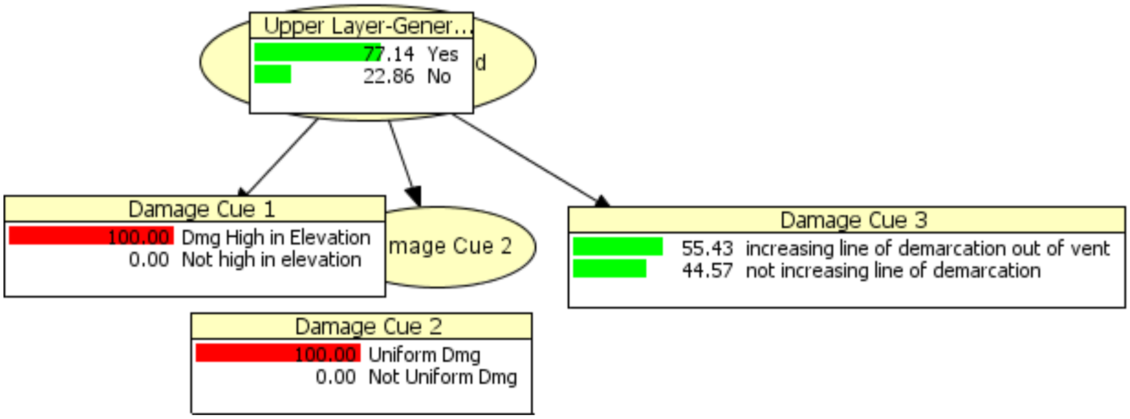


Figure F-65: FP1, 4000kW, 360 seconds, Fire Pattern 1, Upper Layer Generated BN

Fire Pattern 1 – Ventilation-Generated:

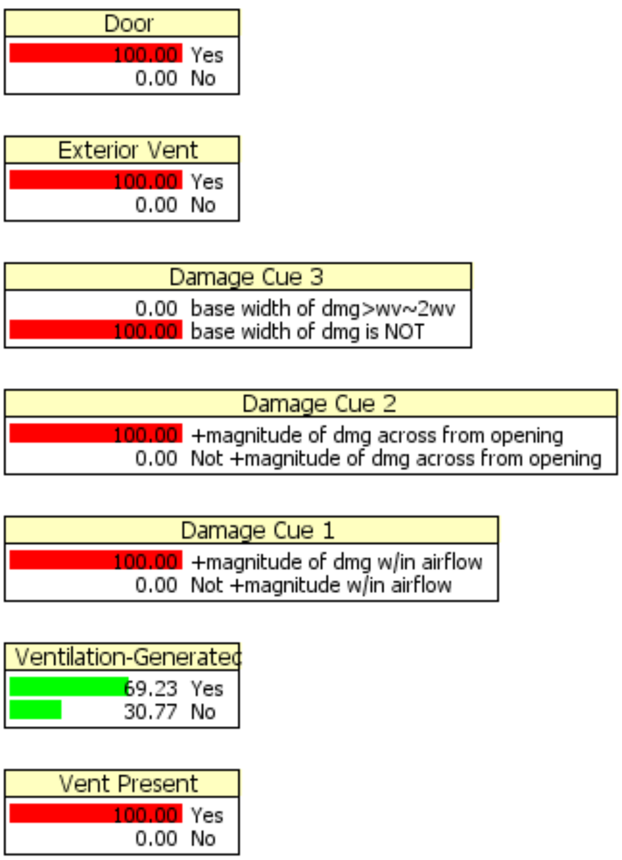


Figure F-66: FP1, 4000kW, 360 seconds, Fire Pattern 1, Ventilation Generated Probabilities

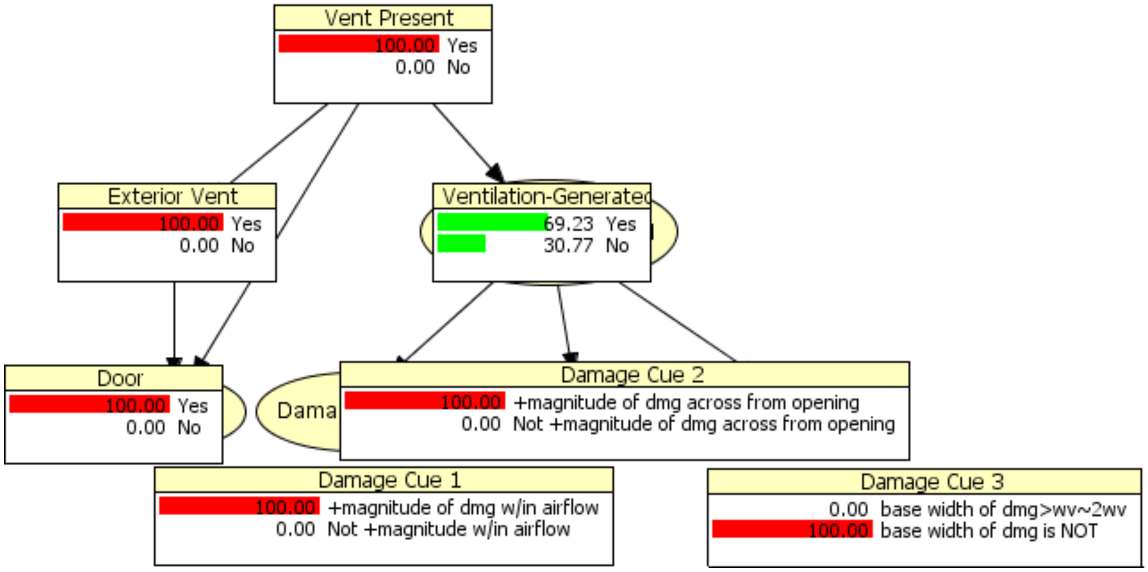


Figure F-67: FP1, 4000kW, 360 seconds, Fire Pattern 1, Ventilation Generated BN

Fire Pattern 2 – Plume Generated:

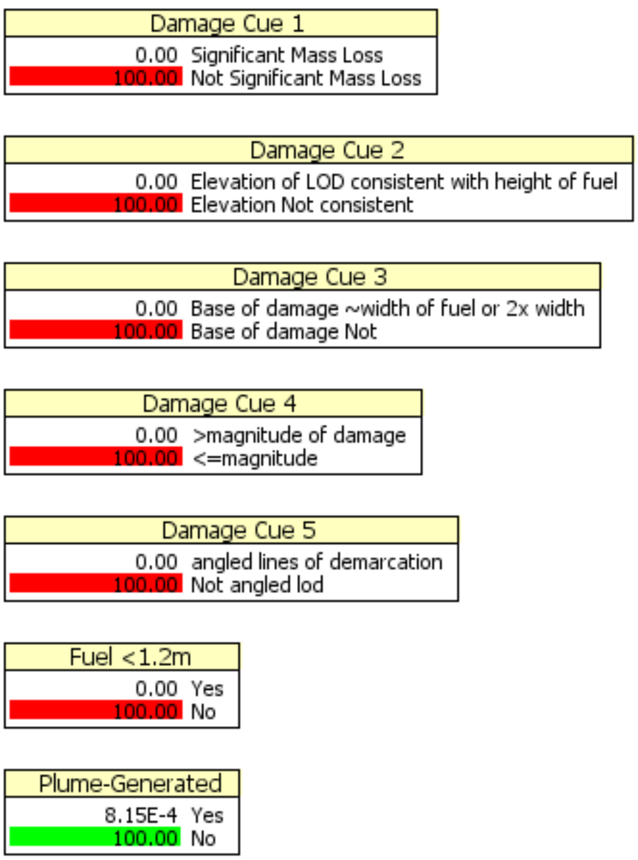


Figure F-68: FP1, 4000kW, 360 seconds, Fire Pattern 2, Plume Generated Probabilities

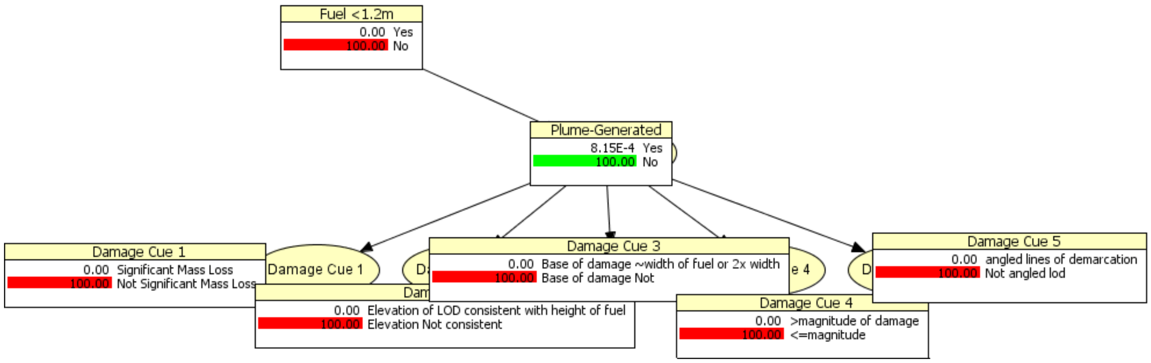


Figure F-69: FP1, 4000kW, 360 seconds, Fire Pattern 2, Plume Generated BN

Fire Pattern 2 – Upper Layer Generated:

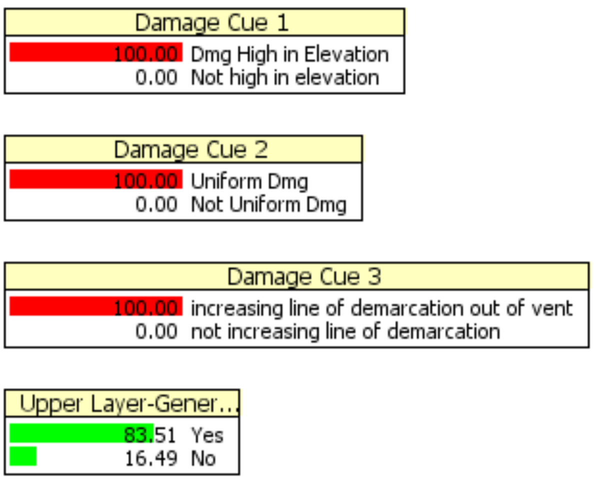


Figure F-70: FP1, 4000kW, 360 seconds, Fire Pattern 2, Upper Layer Generated Probabilities

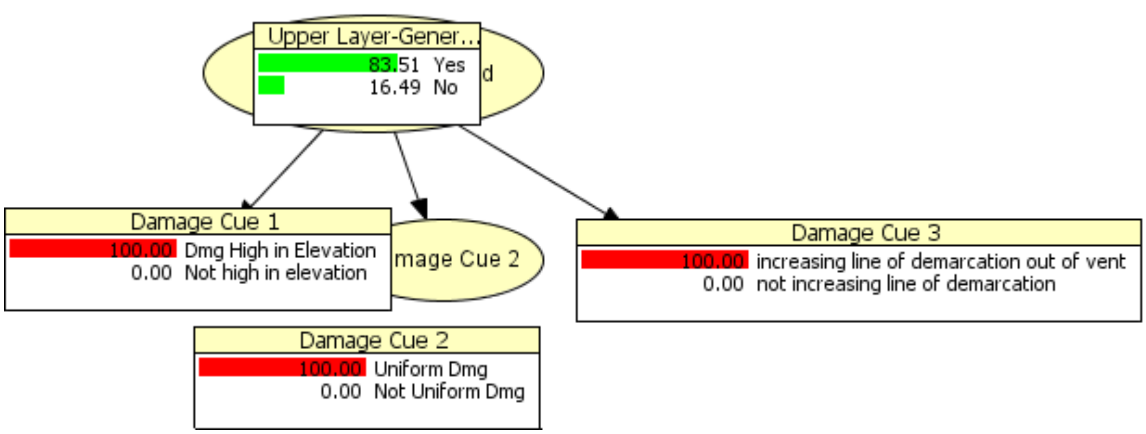


Figure F-71: FP1, 4000kW, 360 seconds, Fire Pattern 2, Upper Layer Generated BN

Fire Pattern 2 – Ventilation-Generated:

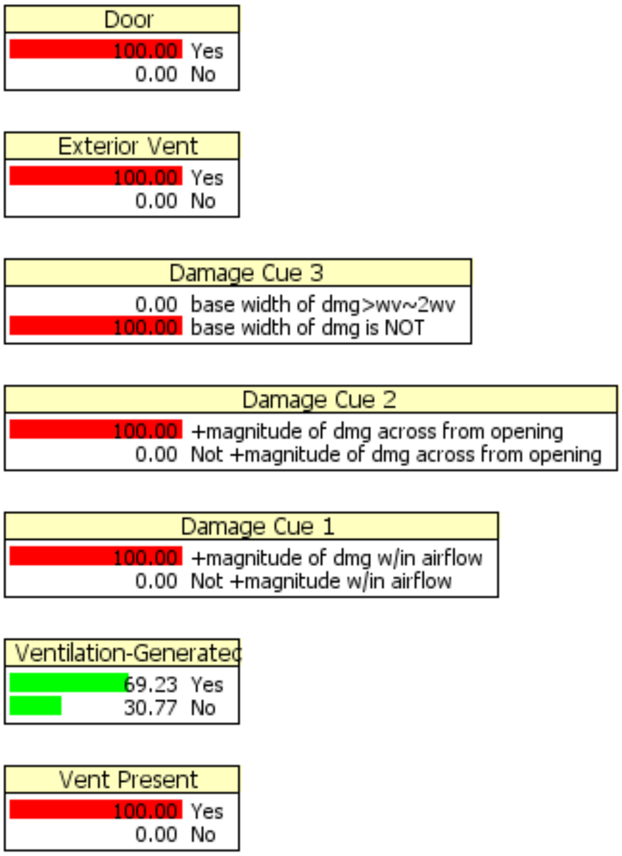


Figure F-72: FP1, 4000kW, 360 seconds, Fire Pattern 2, Ventilation Generated Probabilities

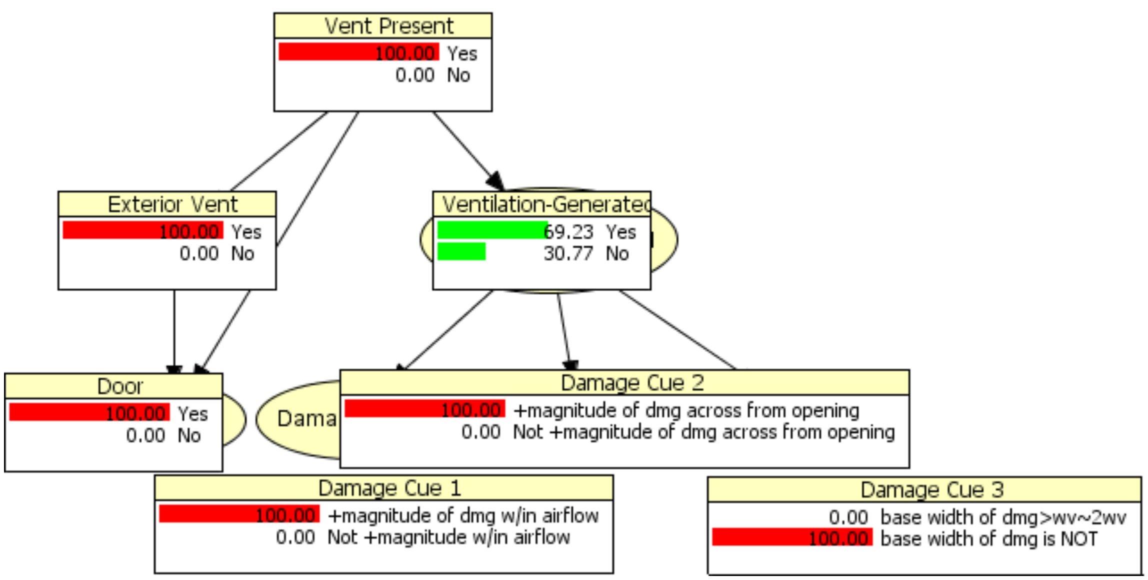


Figure F-73: FP1, 4000kW, 360 seconds, Fire Pattern 2, Ventilation Generated BN

Fire Pattern 3 – Plume Generated:

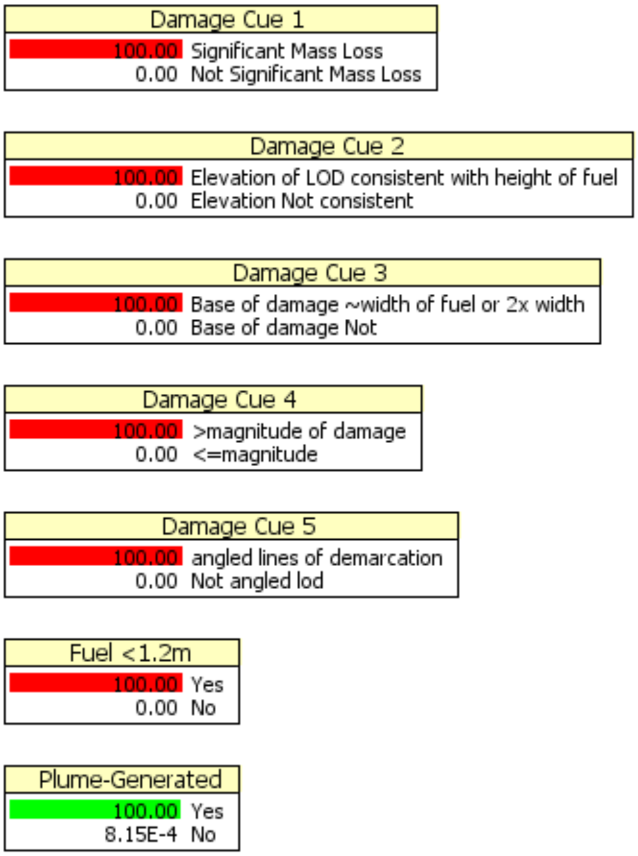


Figure F-74: FP1, 4000kW, 360 seconds, Fire Pattern 3, Plume Generated Probabilities

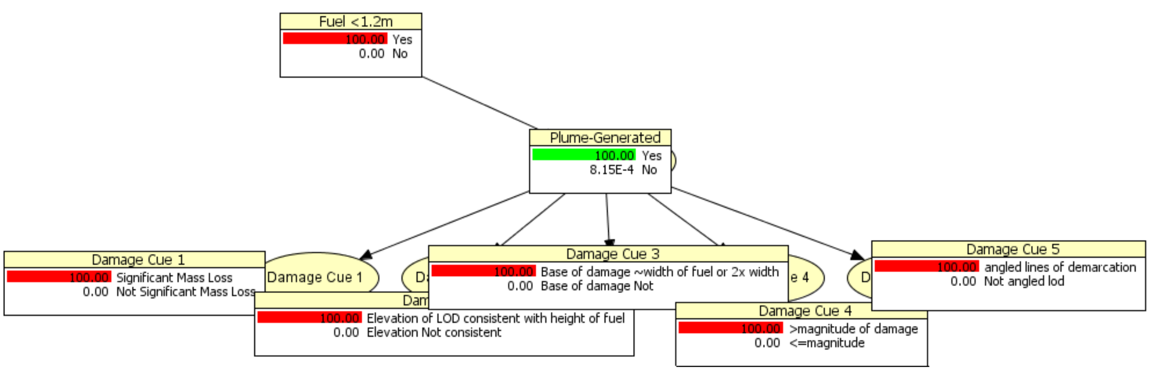


Figure F-75: FP1, 4000kW, 360 seconds, Fire Pattern 3, Plume Generated BN

Fire Pattern 3 – Upper Layer Generated:

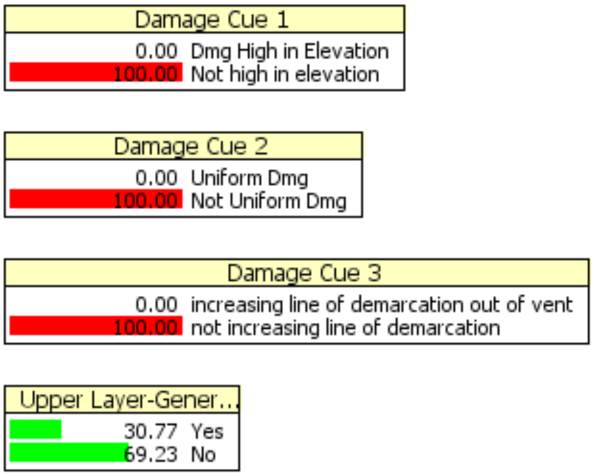


Figure F-76: FP1, 4000kW, 360 seconds, Fire Pattern 3, Upper Layer Generated Probabilities

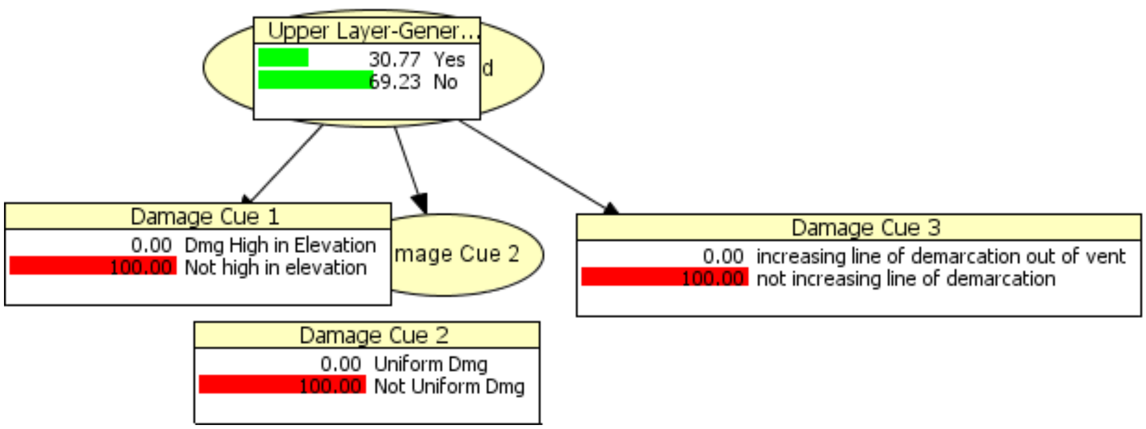


Figure F-77: FP1, 4000kW, 360 seconds, Fire Pattern 3, Upper Layer Generated BN

Fire Pattern 3 – Ventilation-Generated:

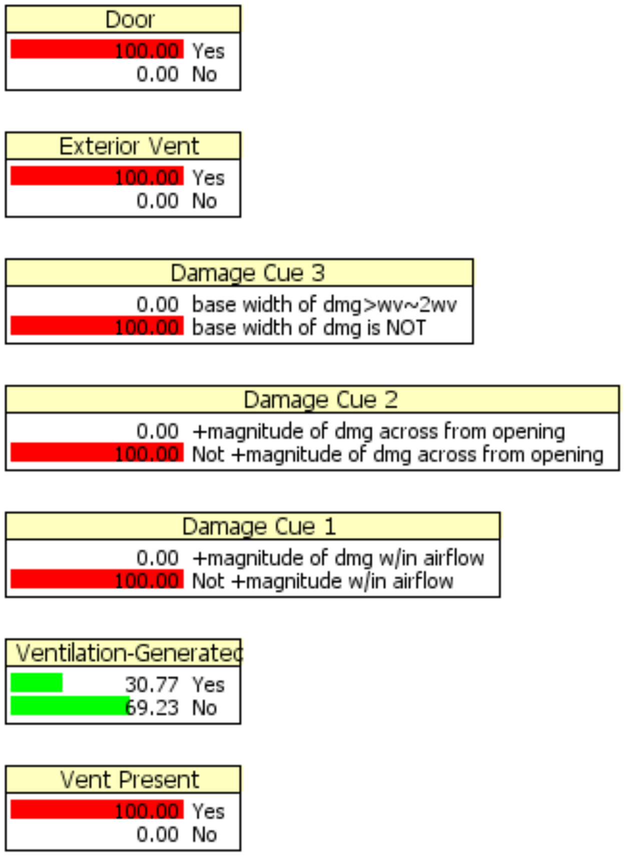


Figure F-78: FP1, 4000kW, 360 seconds, Fire Pattern 3, Ventilation Generated Probabilities

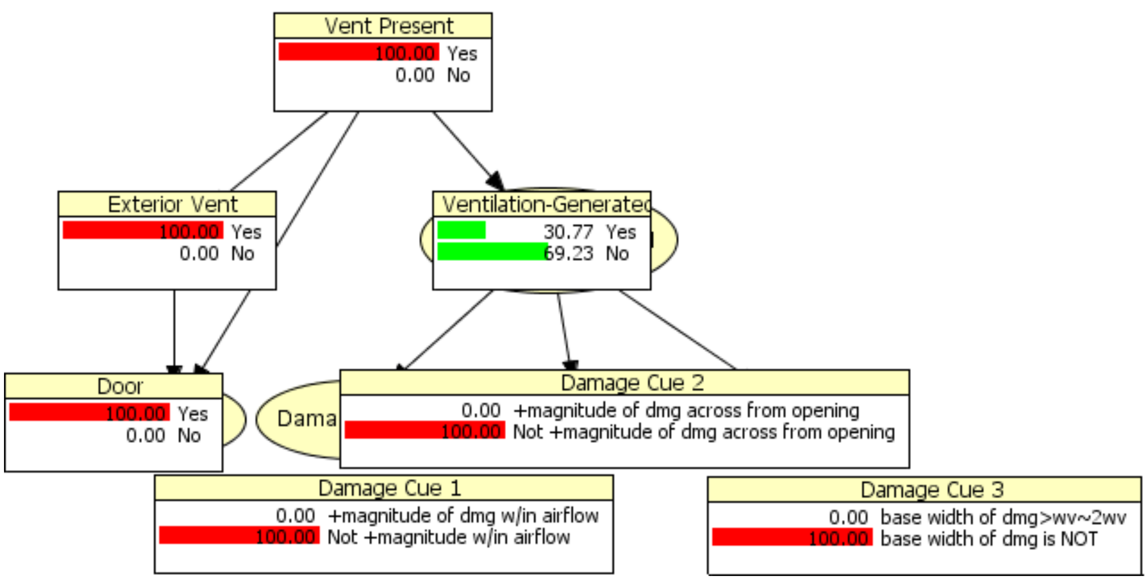


Figure F-79: FP1, 4000kW, 360 seconds, Fire Pattern 3, Ventilation Generated BN

Fire Pattern 4 – Plume Generated:

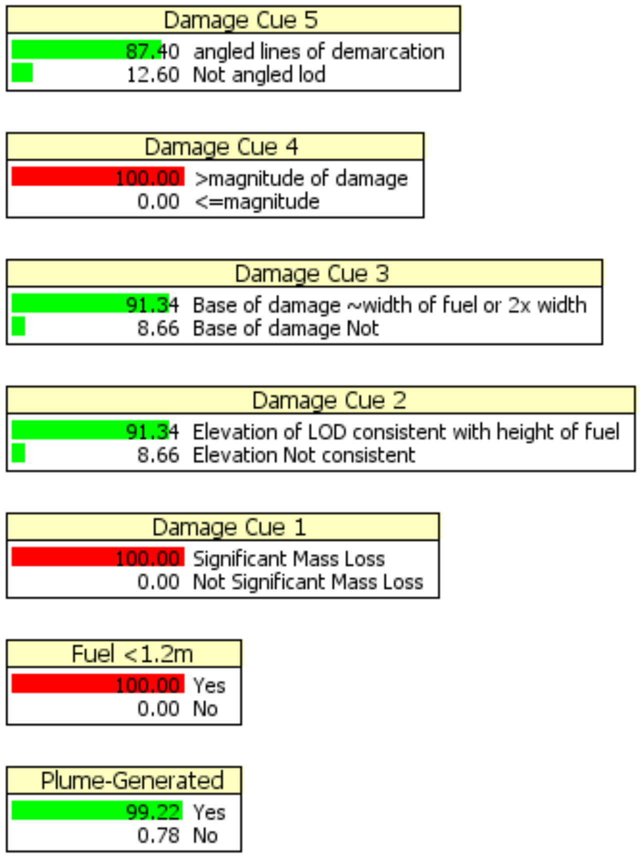


Figure F-80: FP1, 4000kW, 360 seconds, Fire Pattern 4, Plume Generated Probabilities

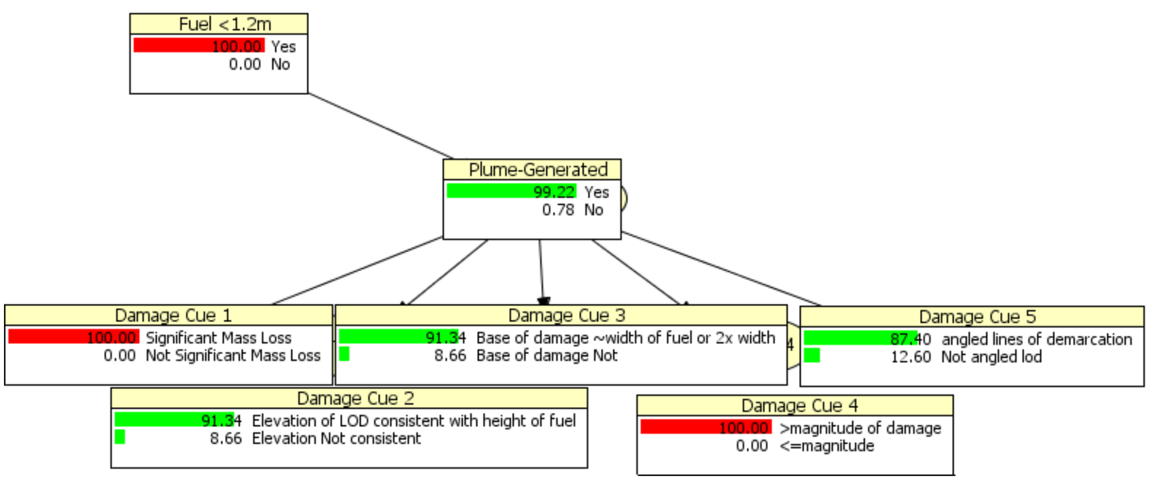


Figure F-81: FP1, 4000kW, 360 seconds, Fire Pattern 4, Plume Generated BN

Fire Pattern 4 – Upper Layer Generated:

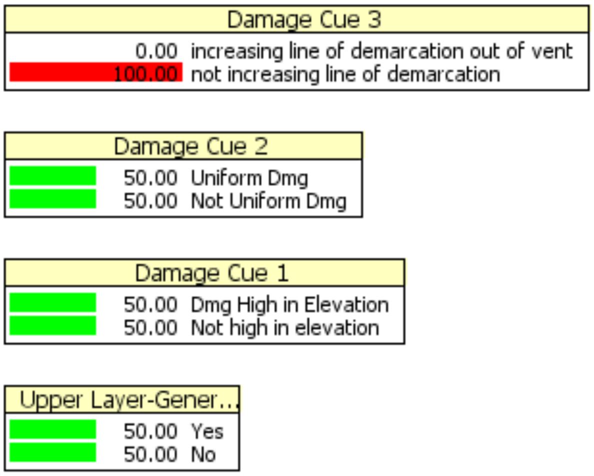


Figure F-82: FP1, 4000kW, 360 seconds, Fire Pattern 4, Upper Layer Generated Probabilities

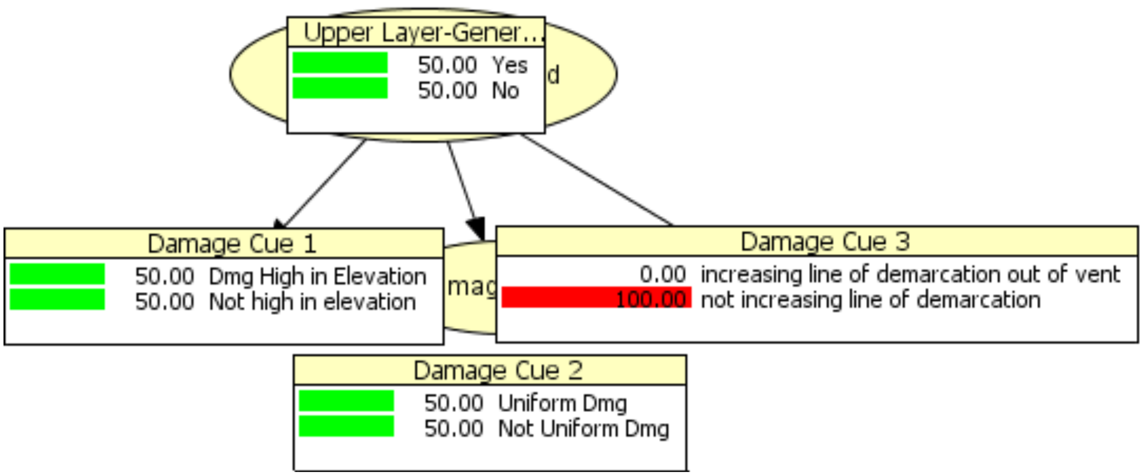


Figure F-83: FP1, 4000kW, 360 seconds, Fire Pattern 4, Upper Layer Generated BN

Fire Pattern 4 – Ventilation-Generated:

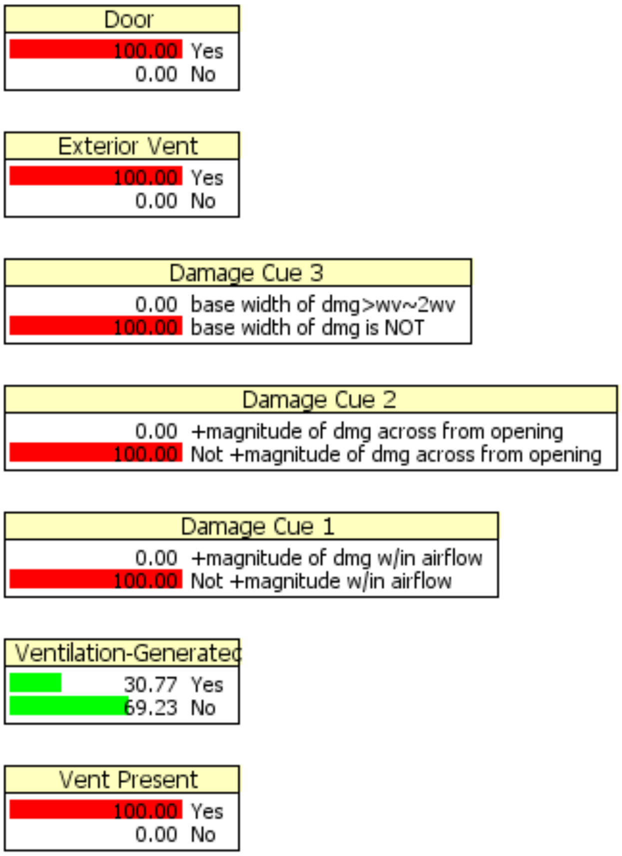


Figure F-84: FP1, 4000kW, 360 seconds, Fire Pattern 4, Ventilation Generated Probabilities

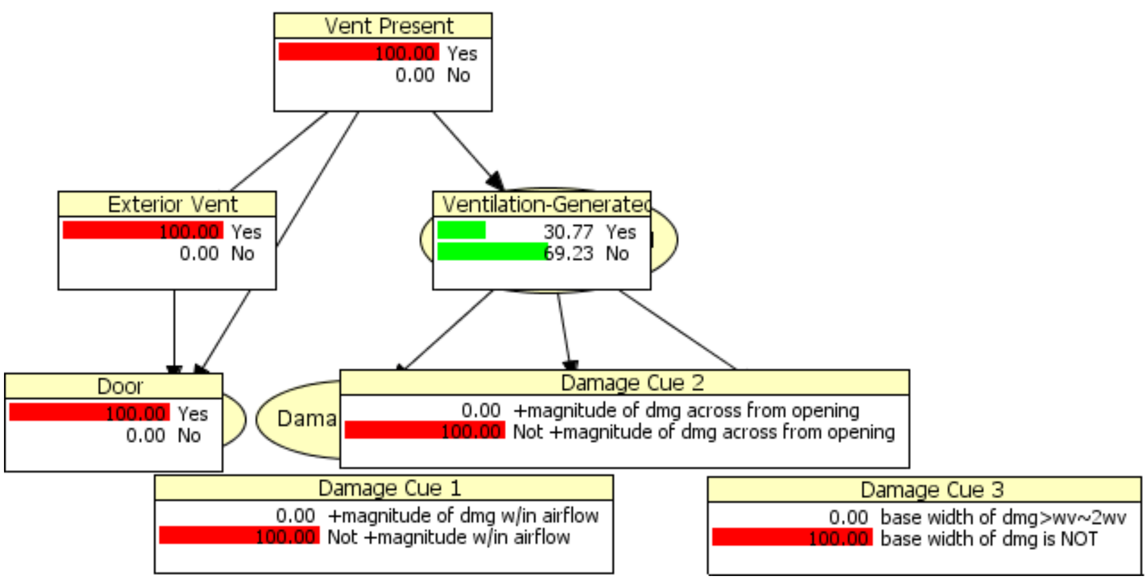


Figure F-85: FP1, 4000kW, 360 seconds, Fire Pattern 4, Ventilation Generated BN

Fire Position 1, 4000 kW, 900 seconds

Fire Pattern 1 – Plume Generated:

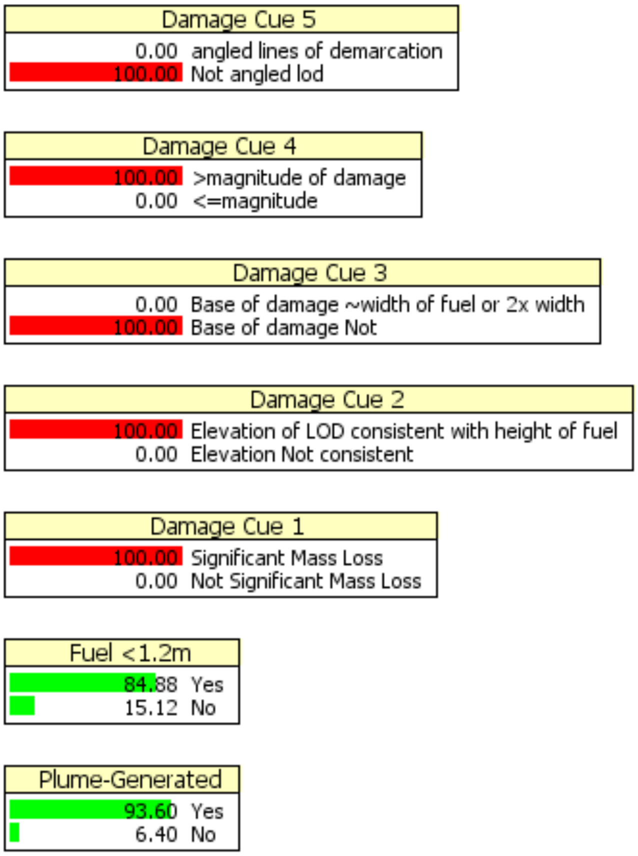


Figure F-86: FP1, 4000kW, 900 seconds, Fire Pattern 1, Plume Generated Probabilities

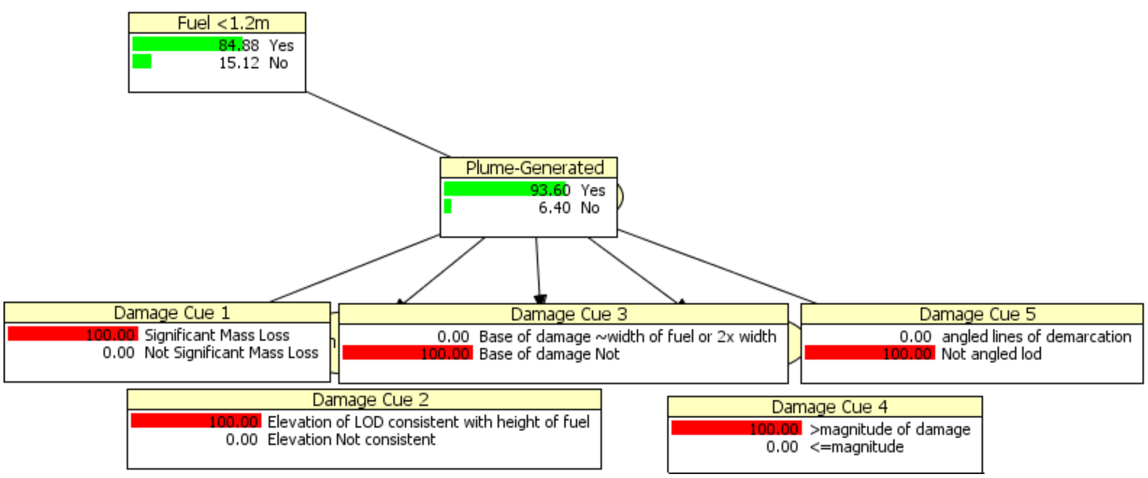


Figure F-87: FP1, 4000kW, 900 seconds, Fire Pattern 1, Plume Generated BN

Fire Pattern 1 – Upper Layer Generated:

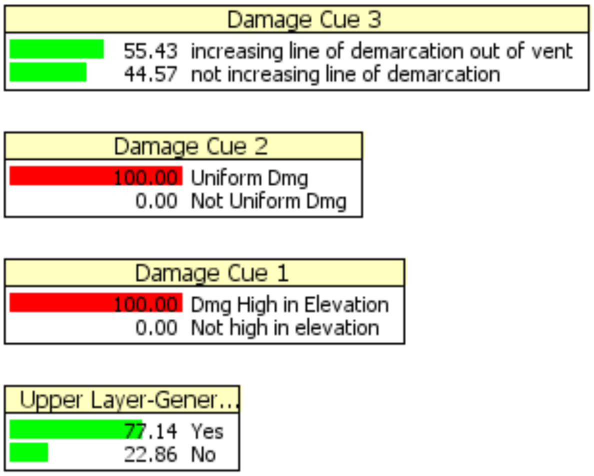


Figure F-88: FP1, 4000kW, 900 seconds, Fire Pattern 1, Upper Layer Generated Probabilities

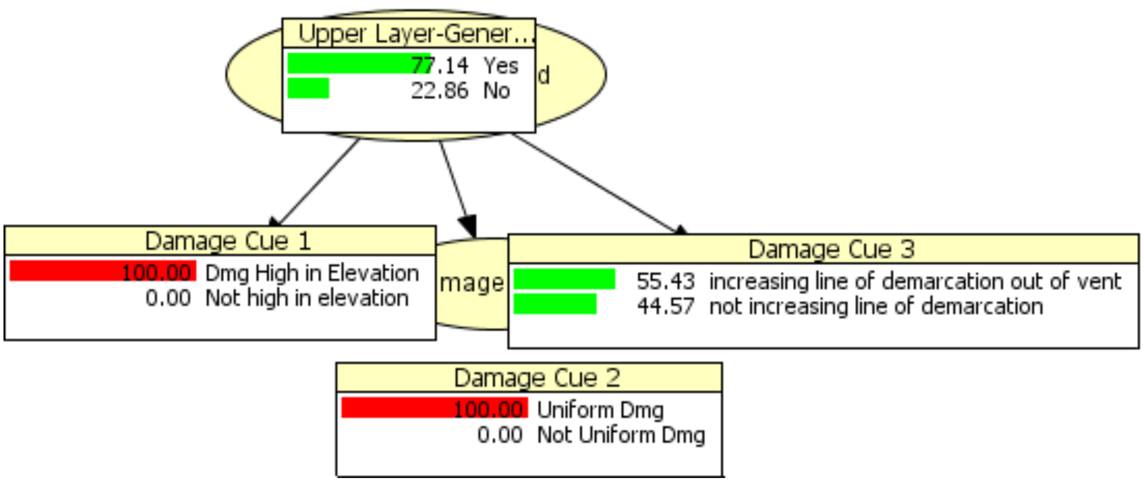


Figure F-89: FP1, 4000kW, 900 seconds, Fire Pattern 1, Upper Layer Generated BN

Fire Pattern 1 – Ventilation-Generated:

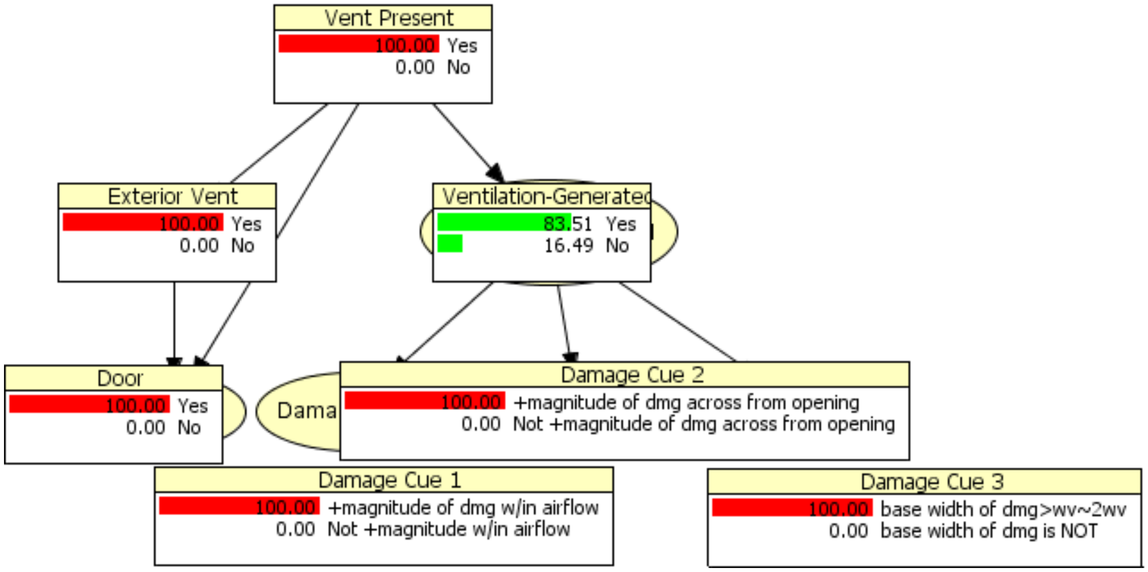


Figure F-90: FP1, 4000kW, 900 seconds, Fire Pattern 1, Ventilation Generated BN

Fire Pattern 2 – Plume Generated:

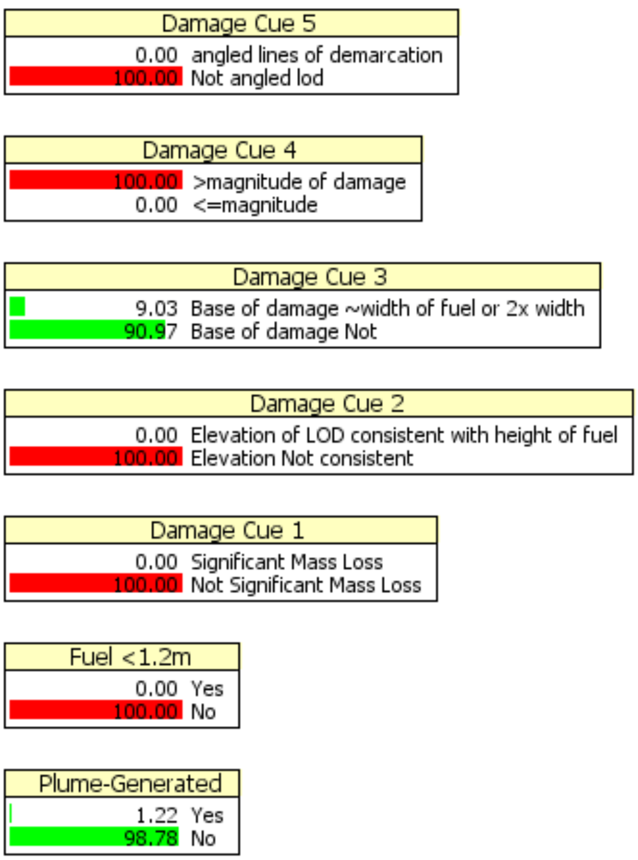


Figure F-91: FP1, 4000kW, 900 seconds, Fire Pattern 2, Plume Generated Probabilities

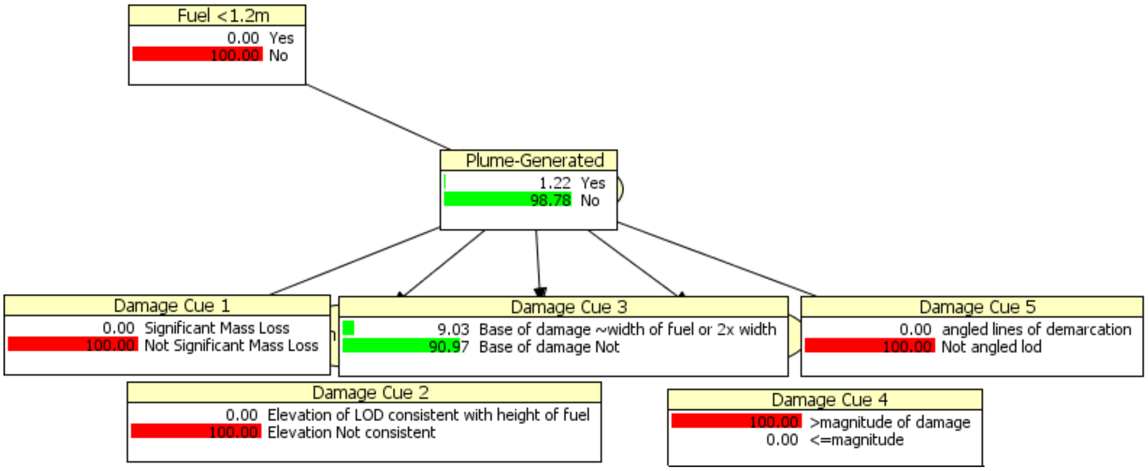


Figure F-92: FP1, 4000kW, 900 seconds, Fire Pattern 2, Plume Generated BN

Fire Pattern 2 – Upper Layer Generated:

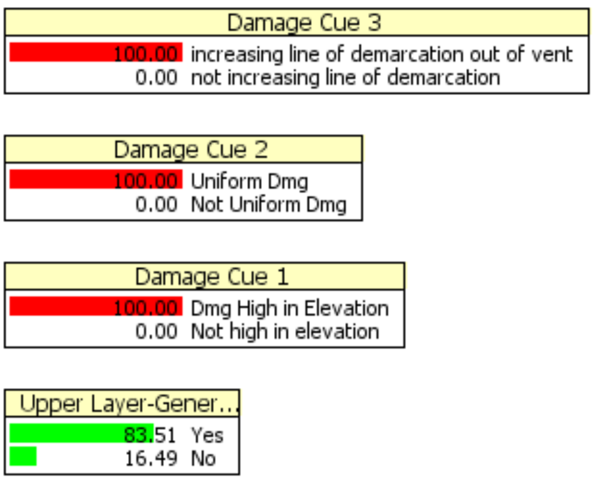


Figure F-93: FP1, 4000kW, 900 seconds, Fire Pattern 2, Upper Layer Generated Probabilities

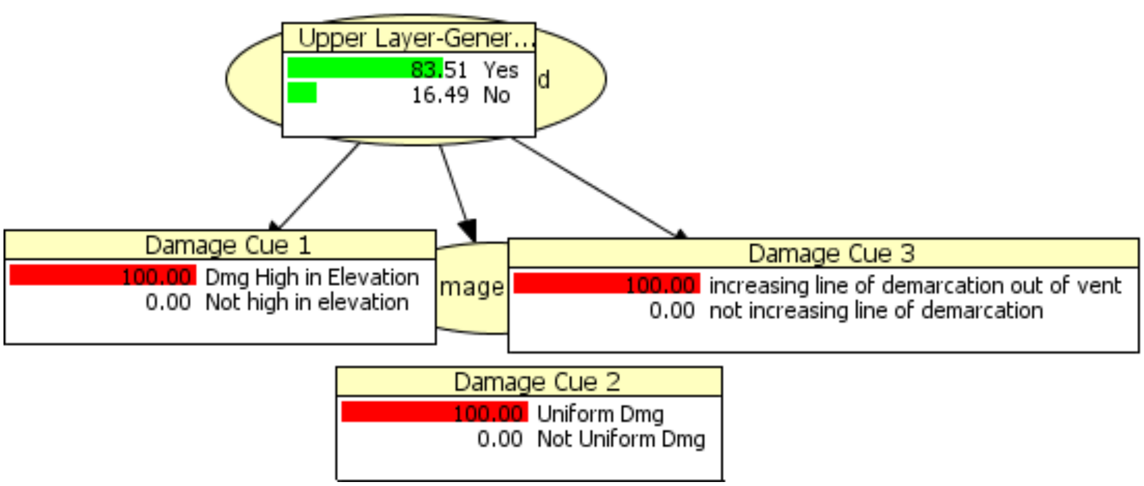


Figure F-94: FP1, 4000kW, 900 seconds, Fire Pattern 2, Upper Layer Generated BN

Fire Pattern 2 – Ventilation-Generated:

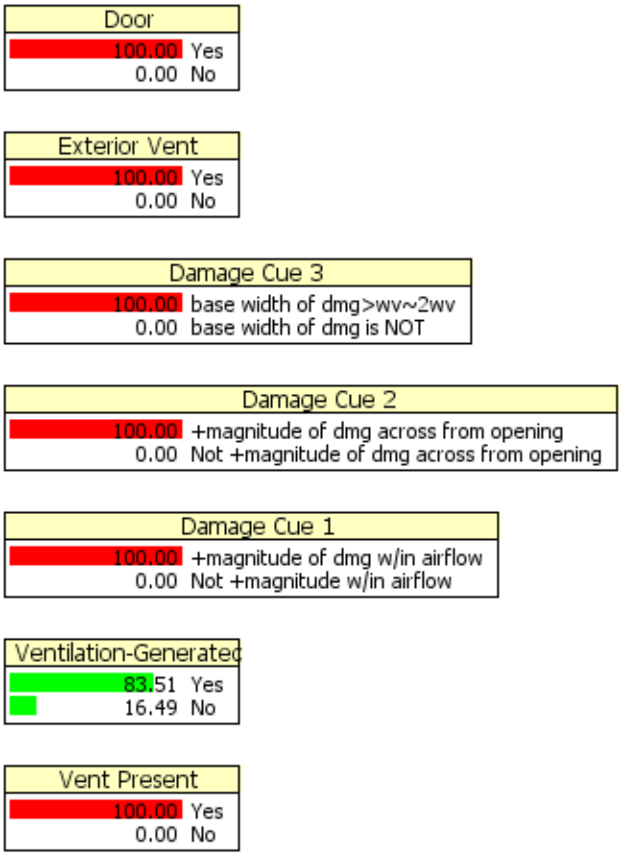


Figure F-95: FP1, 4000kW, 900 seconds, Fire Pattern 2, Ventilation Generated Probabilities

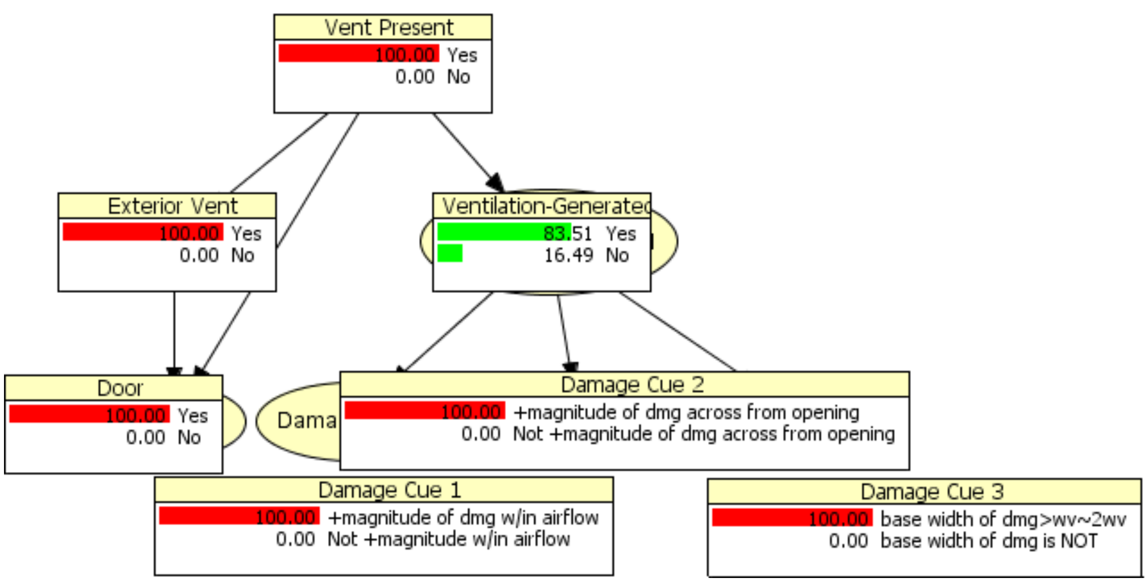


Figure F-96: FP1, 4000kW, 900 seconds, Fire Pattern 2, Ventilation Generated BN

Fire Pattern 3 – Plume Generated:

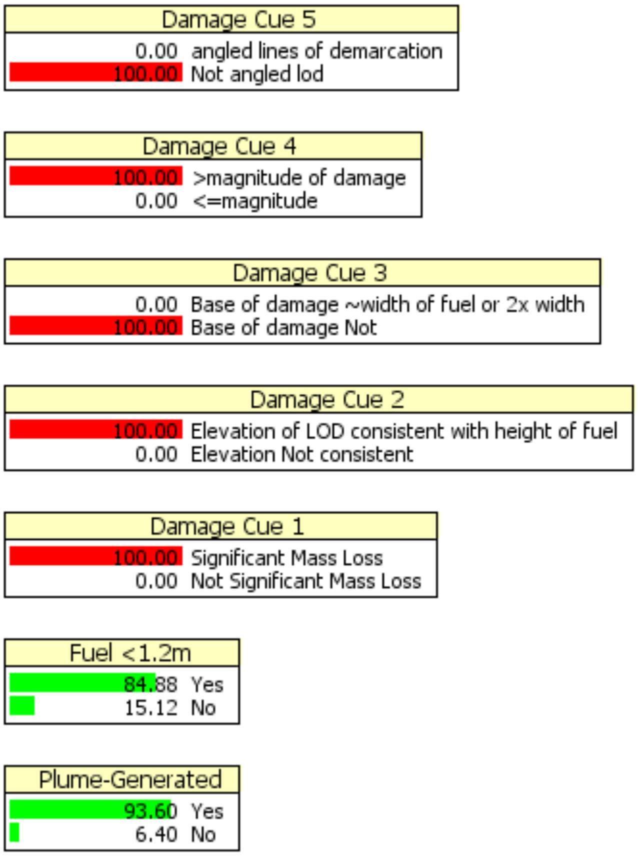


Figure F-97: FP1, 4000kW, 900 seconds, Fire Pattern 3, Plume Generated Probabilities

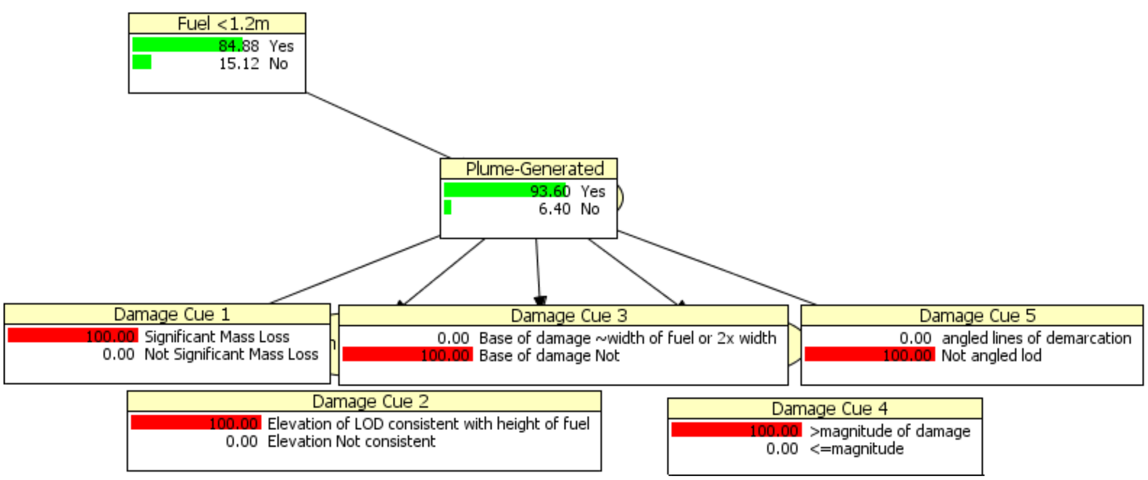


Figure F-98: FP1, 4000kW, 900 seconds, Fire Pattern 3, Plume Generated BN

Fire Pattern 3 – Upper Layer Generated:

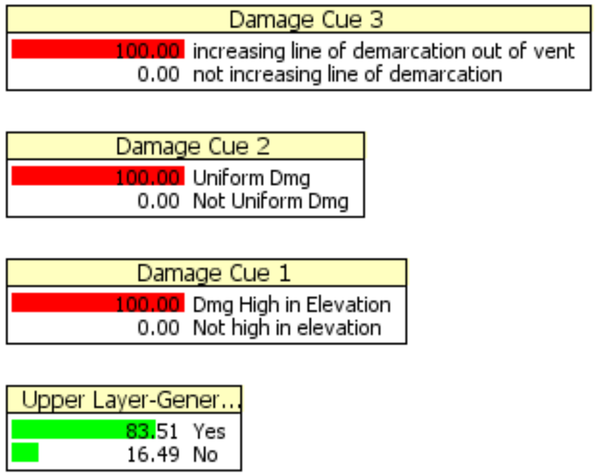


Figure F-99: FP1, 4000kW, 900 seconds, Fire Pattern 3, Upper Layer Generated Probabilities

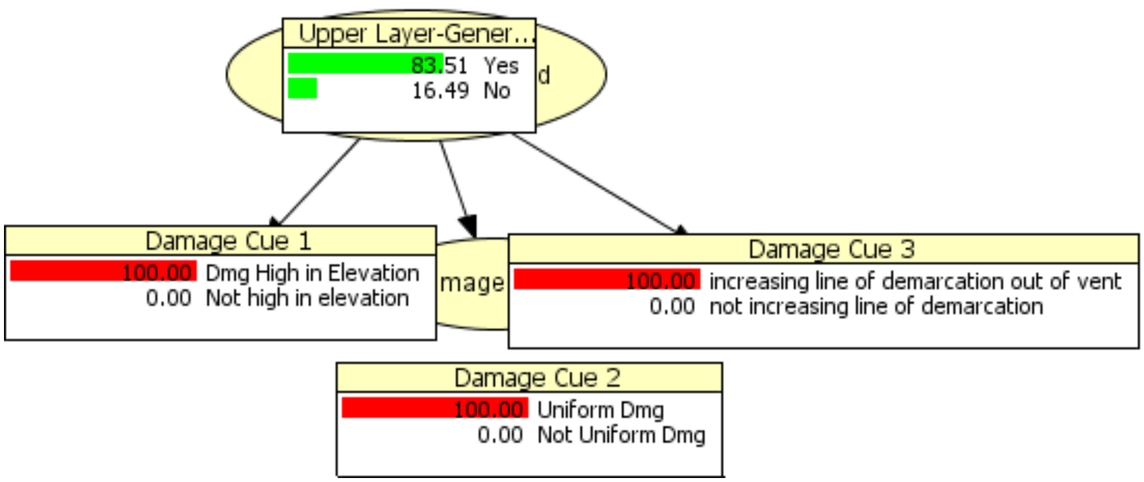


Figure F-100: FP1, 4000kW, 900 seconds, Fire Pattern 3, Upper Layer Generated BN

Fire Pattern 3 – Ventilation-Generated:

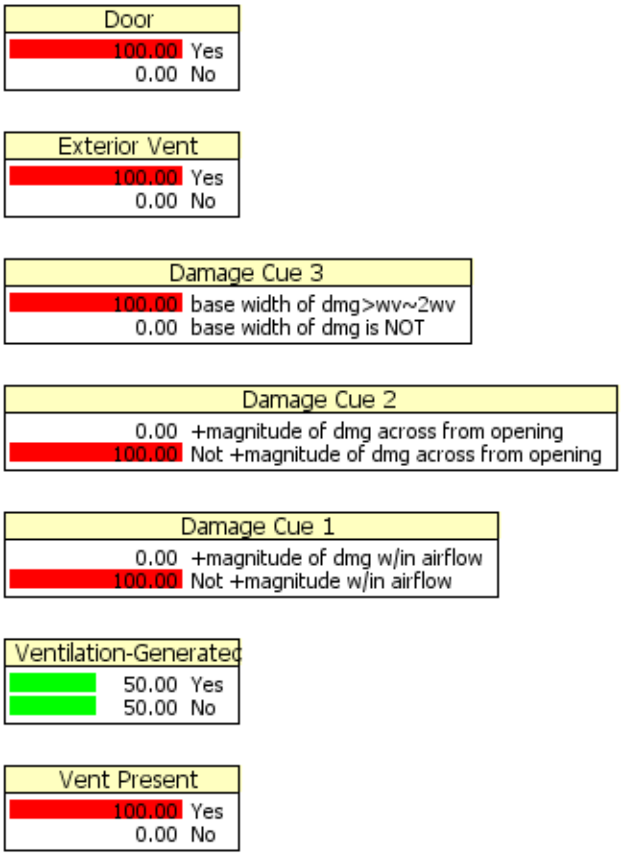


Figure F-101: FP1, 4000kW, 900 seconds, Fire Pattern 3, Ventilation Generated Probabilities

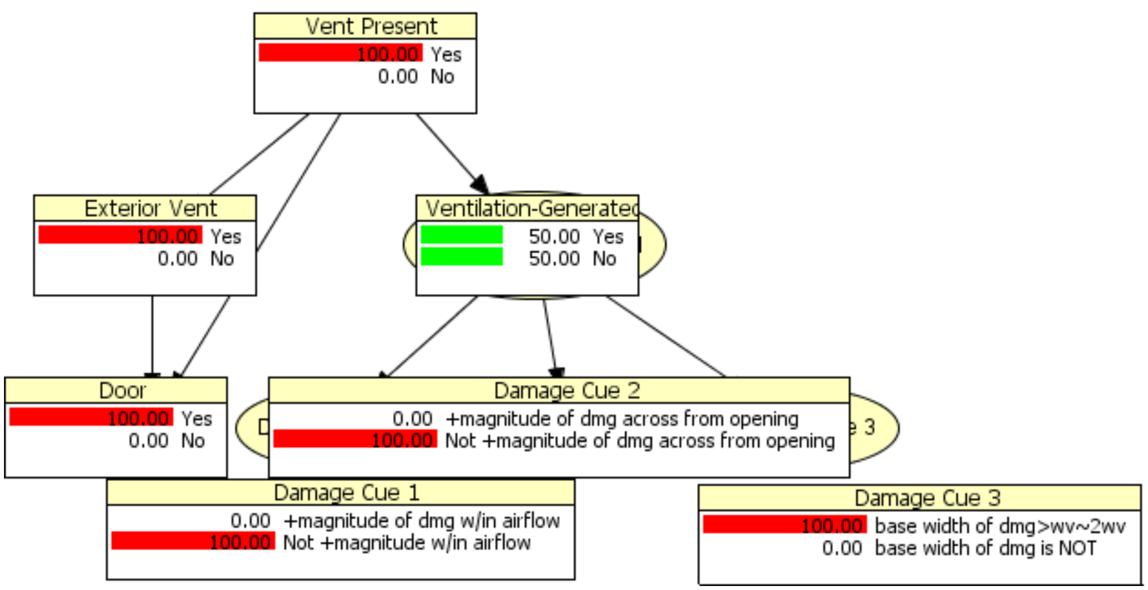


Figure F-102: FP1, 4000kW, 900 seconds, Fire Pattern 3, Ventilation Generated BN

Fire Pattern 4 – Plume Generated:

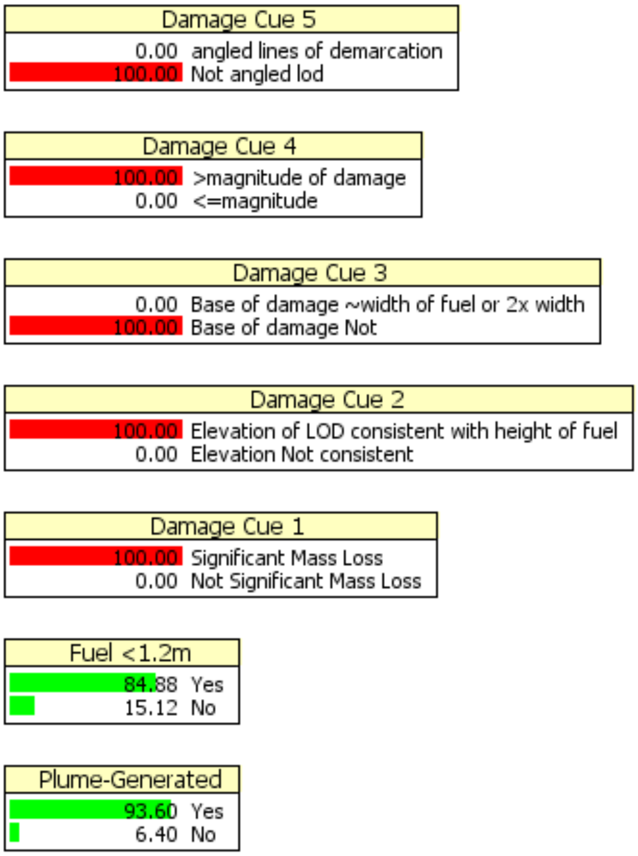


Figure F-103: FP1, 4000kW, 900 seconds, Fire Pattern 4, Plume Generated Probabilities

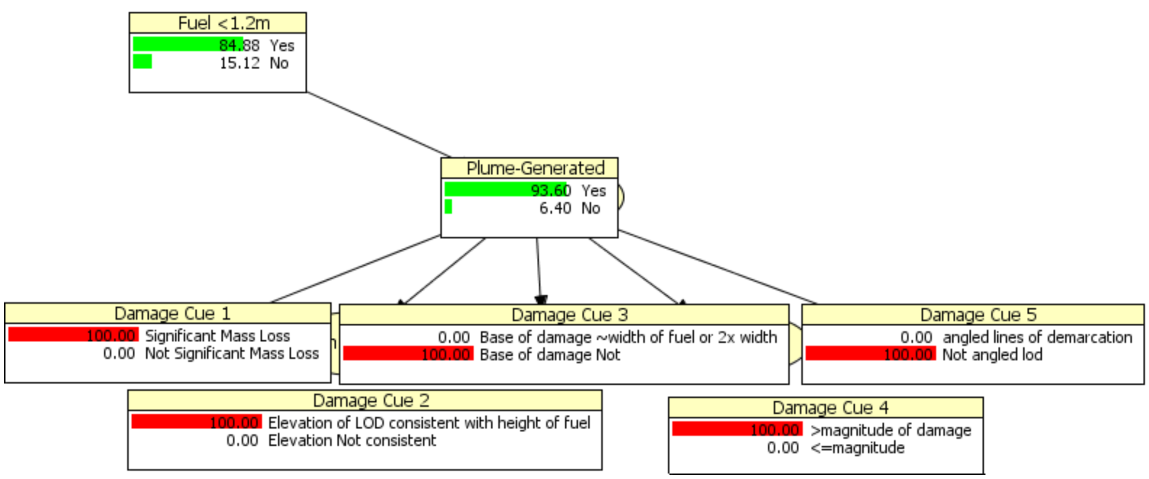


Figure F-104: FP1, 4000kW, 900 seconds, Fire Pattern 4, Plume Generated BN

Fire Pattern 4 – Upper Layer Generated:

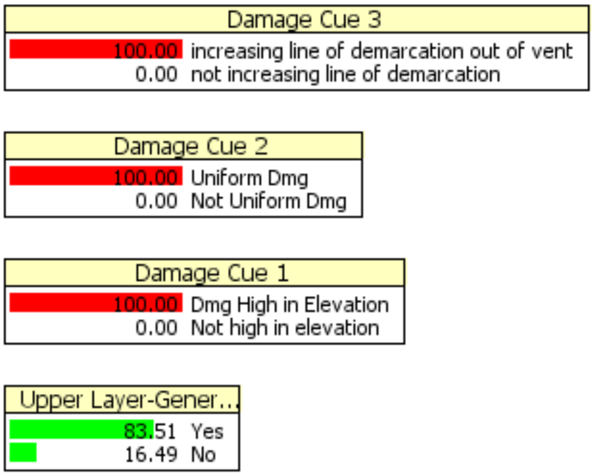


Figure F-105: FP1, 4000kW, 900 seconds, Fire Pattern 4, Upper Layer Generated Probabilities

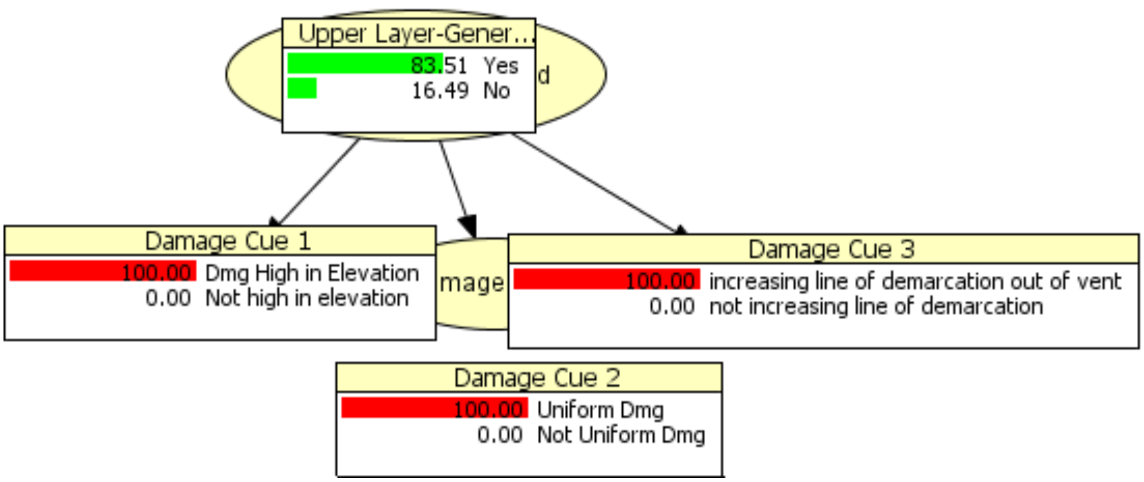


Figure F-106: FP1, 4000kW, 900 seconds, Fire Pattern 4, Upper Layer Generated BN

Fire Pattern 4 – Ventilation-Generated:

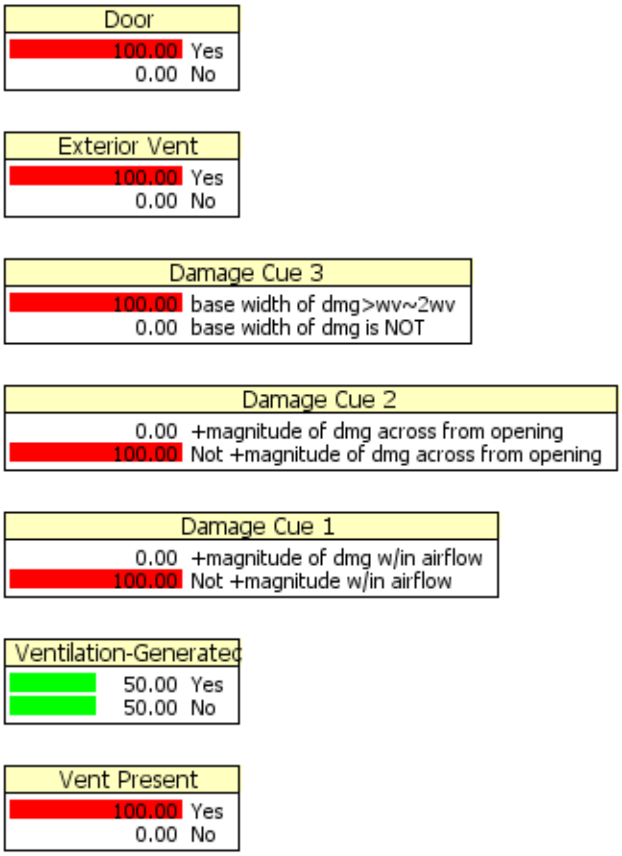


Figure F-107: FP1, 4000kW, 900 seconds, Fire Pattern 4, Ventilation Generated Probabilities

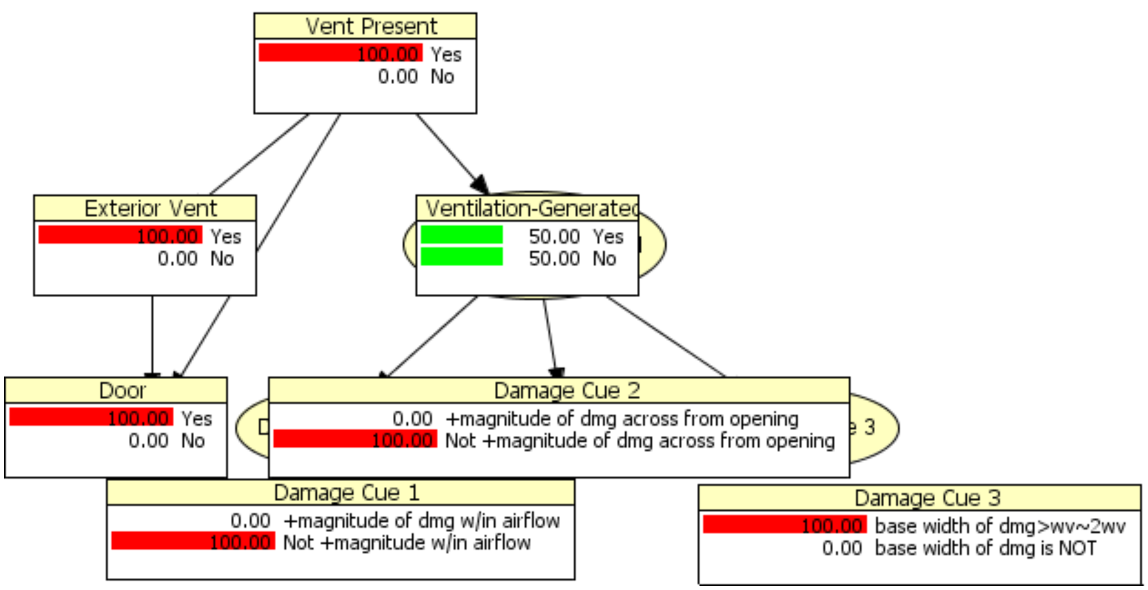


Figure F-108: FP1, 4000kW, 900 seconds, Fire Pattern 4, Ventilation Generated BN

Fire Pattern 5 – Plume Generated:

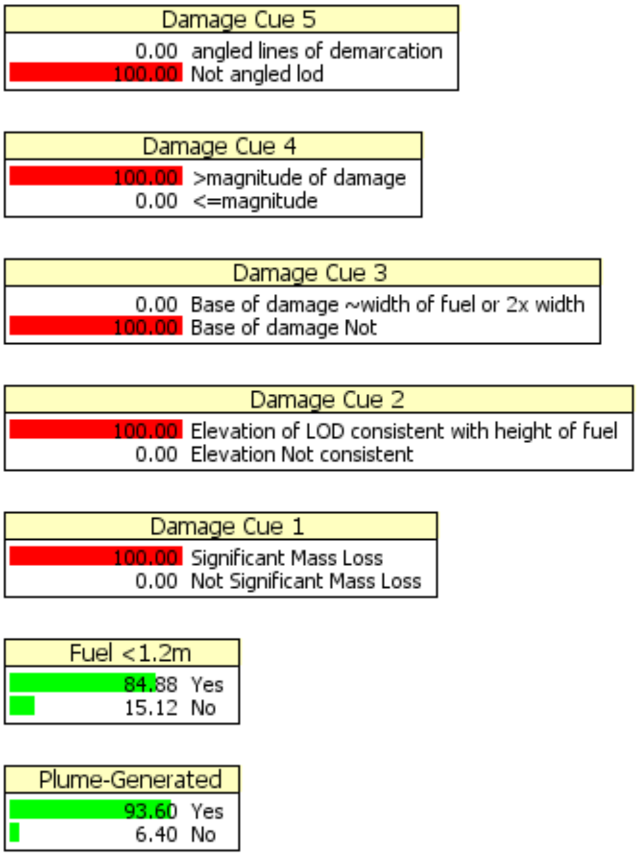


Figure F-109: FP1, 4000kW, 900 seconds, Fire Pattern 5, Plume Generated Probabilities

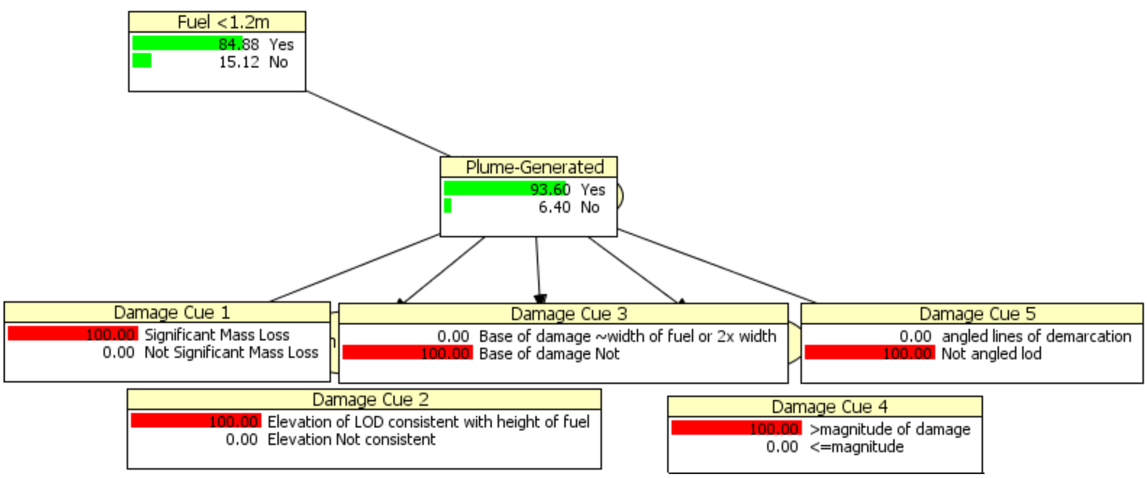


Figure F-110: FP1, 4000kW, 900 seconds, Fire Pattern 5, Plume Generated BN

Fire Pattern 5 – Upper Layer Generated:

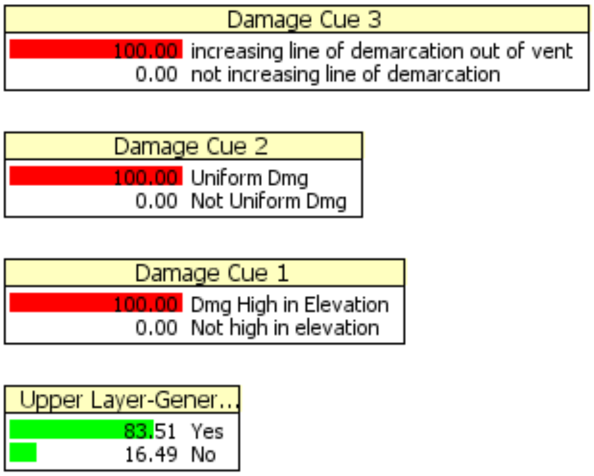


Figure F-111: FP1, 4000kW, 900 seconds, Fire Pattern 5, Upper Layer Generated Probabilities

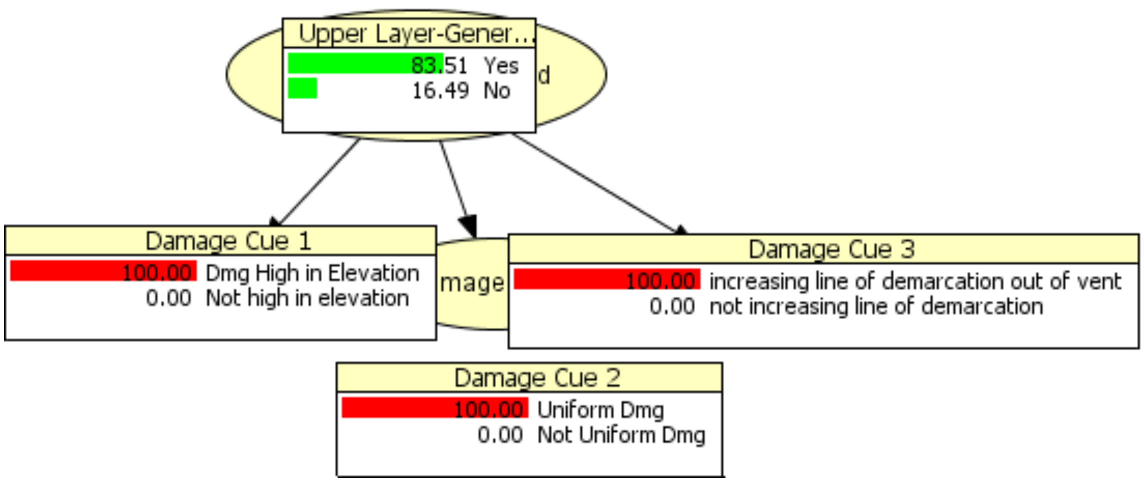


Figure F-112: FP1, 4000kW, 900 seconds, Fire Pattern 5, Upper Layer Generated BN

Fire Pattern 5 – Ventilation-Generated:

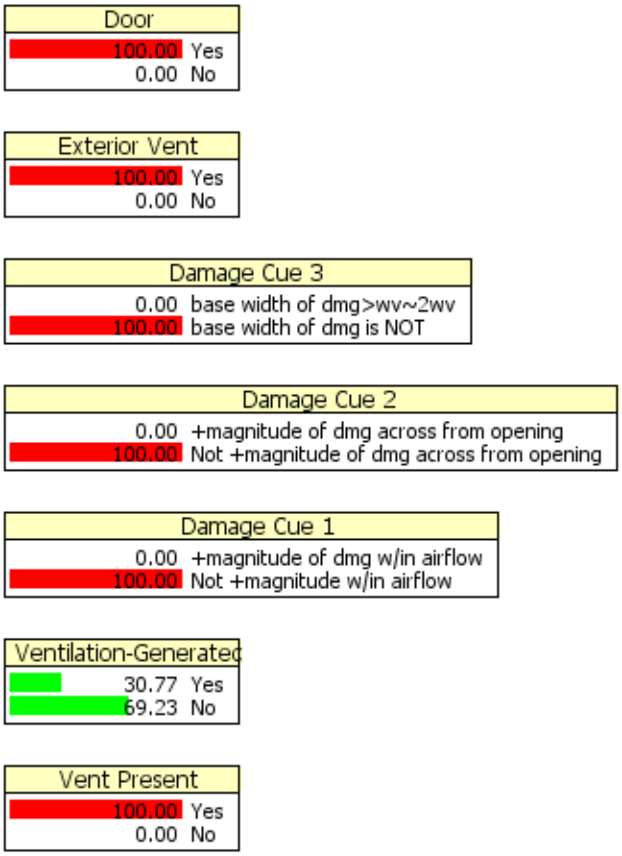


Figure F-113: FP1, 4000kW, 900 seconds, Fire Pattern 5, Ventilation Generated Probabilities

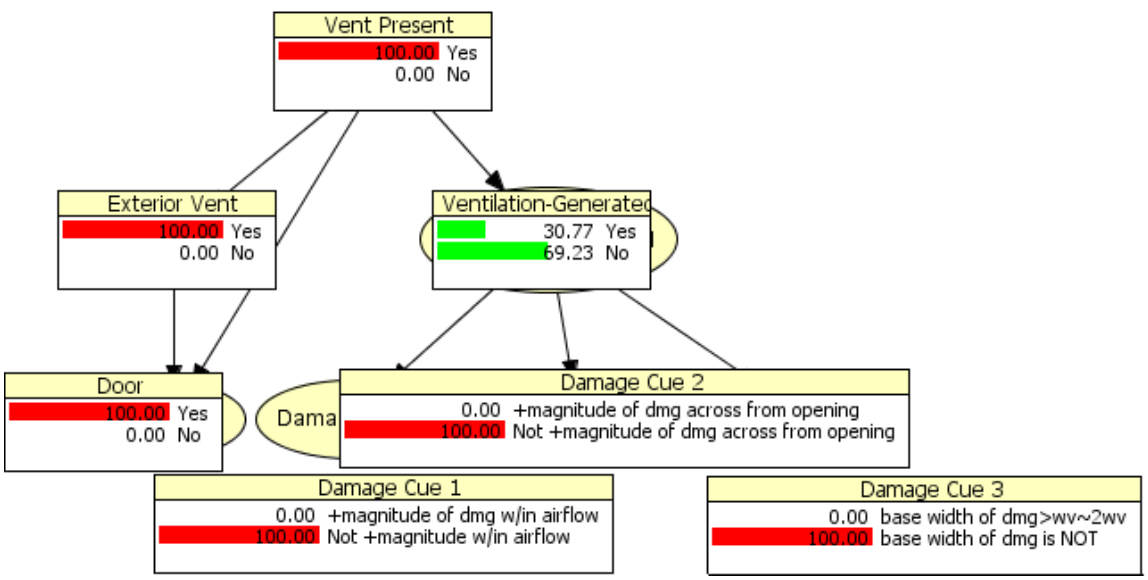


Figure F-114: FP1, 4000kW, 900 seconds, Fire Pattern 5, Ventilation Generated BN

Fire Pattern 6 – Plume Generated:

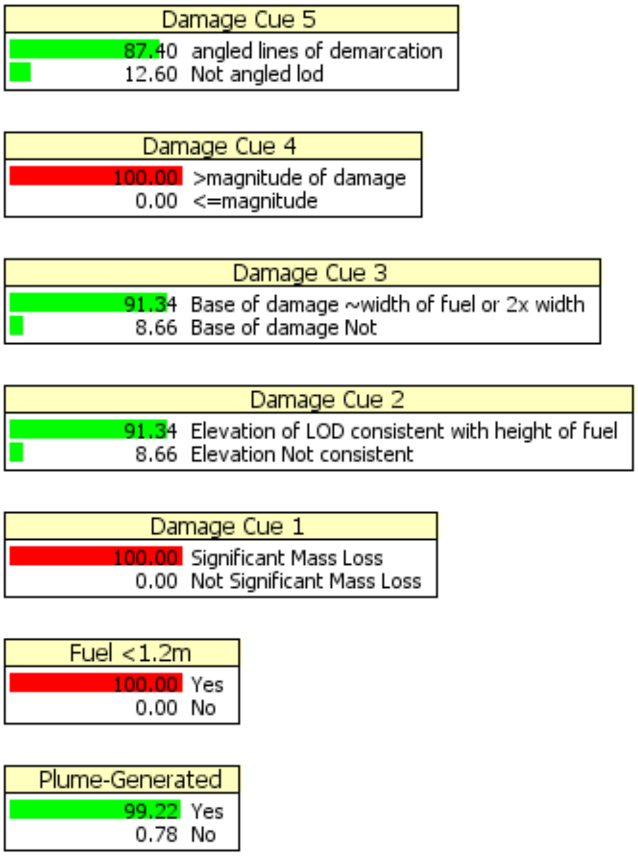


Figure F-115: FP1, 4000kW, 900 seconds, Fire Pattern 6, Plume Generated Probabilities

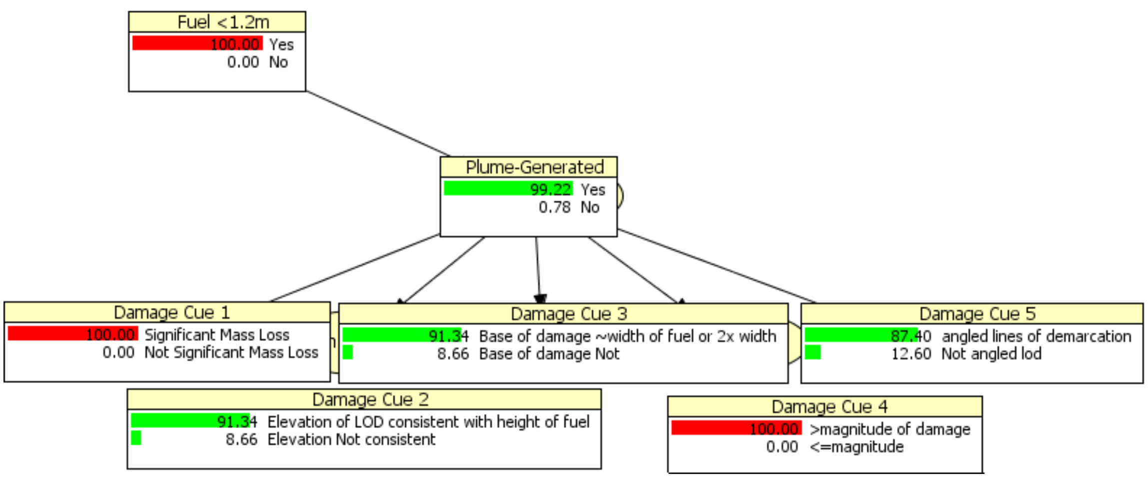


Figure F-116: FP1, 4000kW, 900 seconds, Fire Pattern 6, Plume Generated BN

Fire Pattern 6 – Upper Layer Generated:

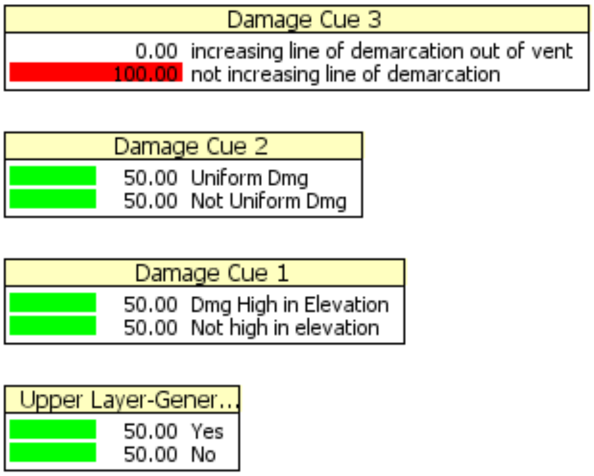


Figure 117: FP1, 4000kW, 900 seconds, Fire Pattern 6, Upper Layer Generated Probabilities

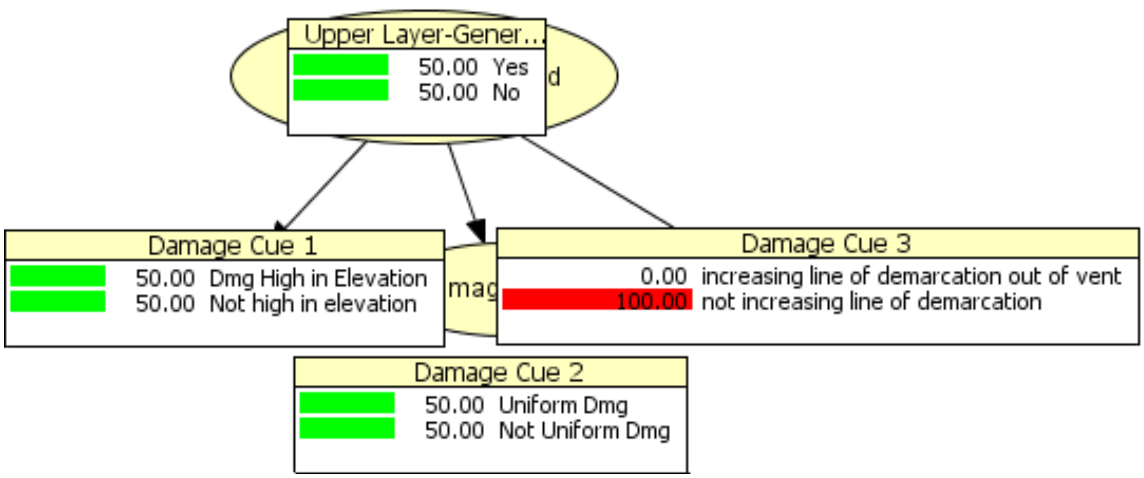


Figure 118: FP1, 4000kW, 900 seconds, Fire Pattern 6, Upper Layer Generated BN

Fire Pattern 6 – Ventilation-Generated:

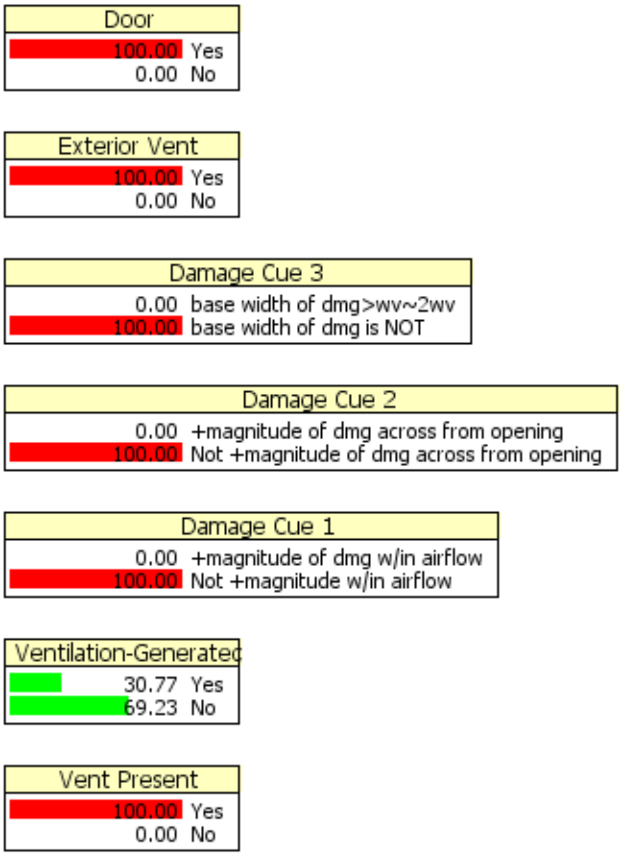


Figure 119: FP1, 4000kW, 900 seconds, Fire Pattern 6, Ventilation Generated Probabilities

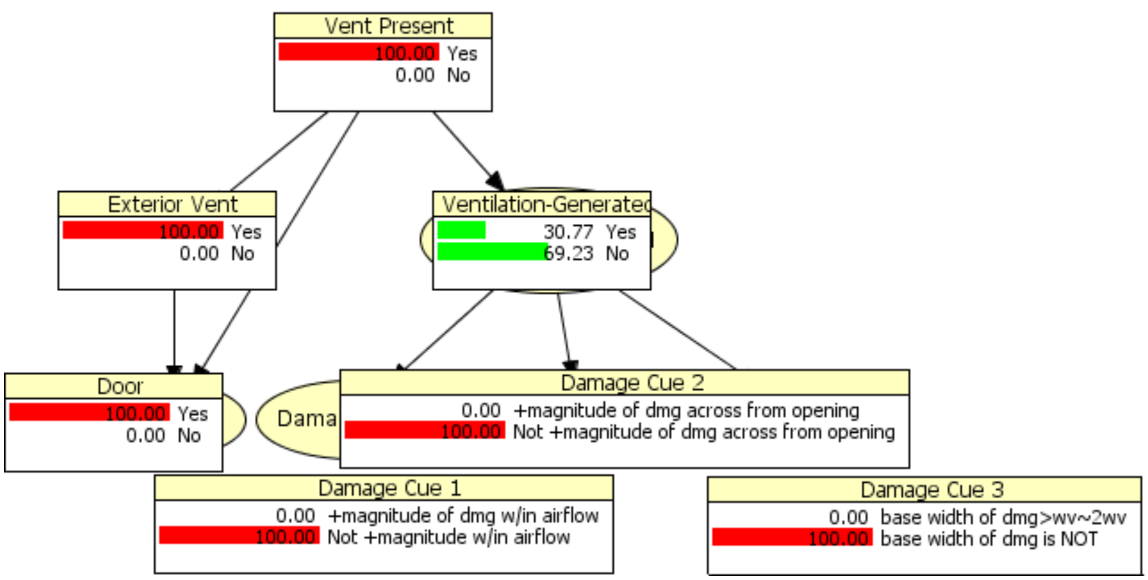


Figure 120: FP1, 4000kW, 900 seconds, Fire Pattern 6, Ventilation Generated BN

APPENDIX G – Reliability and Validity Charts

The two measures used to assess the POD were validity and reliability. This section has been organized into reliability results and validation results. The results for each measure, as outlined in the methods chapter, will be described below.

G.1 Reliability Charts

The reliability measure examined the consistency of participants arriving at the same determination for location of the true origin. The distances between the X- and Y-coordinate selected by the participants as location of origin and the true coordinate for origin was calculated for each of the 32 scenarios. While this measure does not incorporate directionality, we can conclude that the POD group is more consistent in their selection of origin if the variability of the distances is smaller for the participants utilizing the POD compared to those using no POD.

The variance (σ^2) is a measure of how far numbers are spread out, which should provide a good measure for comparing the reliability of the POD in comparison to those that did not use the POD. The variance of the given answers by the participants without the POD was compared to the variance with the participants using the POD. The variability in distances was compared from the participants' selected center of origin and the true center of origin to determine if those using the POD are answering "closer together." The F-test was used for equality of variances between those not using the method and those using the POD. That test was insignificant at the .05 level (p=.9). However, a decrease in variability was seen at the individual scenarios level. In 21 of the 32 scenarios (66%), the variability in those distances was smaller for those using the POD than those not using the POD (Tables G-1-G-2).

Table G-1: Reliability Measures-Overall Variability Change

	Number of Scenarios	Total scenarios	%
Decreasing variability w/POD	21	32	66
Increasing variability w/POD	11	32	34

Table G-2: Reliability Measures-Test for Equality of Variances

	Without POD	With POD
Mean (μ) distance from true origin	105.46	86.93
Standard Deviation (σ)	10.81	10.58
Median distance from true origin	105.79	88.98
Folded F test	F=1.04	p=.9

To better evaluate any trends with the data, the variance is plotted for each fire position. The general trend with the simulation data was a decrease in variability with the lower duration and lower peak heat release rate fires, with a few exceptions. The greatest variability was consistently observed with the highest heat release rate simulations at the longest durations. This was expected based on previous review of the literature. The higher the heat release rate and the longer the duration of burning past ventilation-controlled conditions results in a greater variability in the answers (Figures G-1 through G-5). There were 19 of 30 simulation scenarios (63%) that demonstrated less variability when using the POD in comparison to answers provided without using the POD. Both physical experiments had a decrease in variability when the POD was used (Figure G-6).

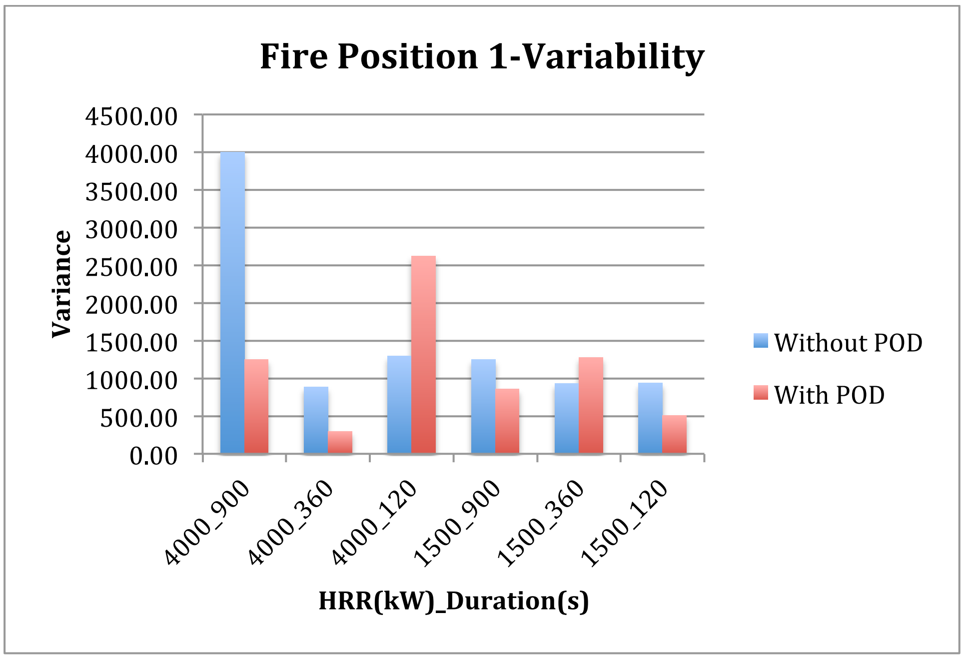


Figure G-1: Fire Position 1-Variability

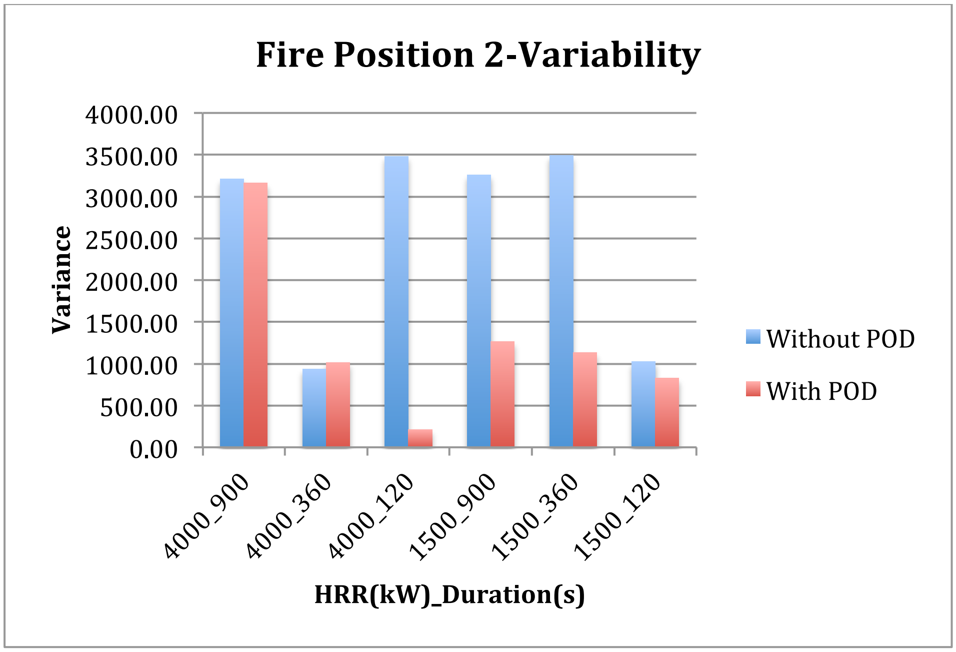


Figure G-2: Fire Position 2-Variability

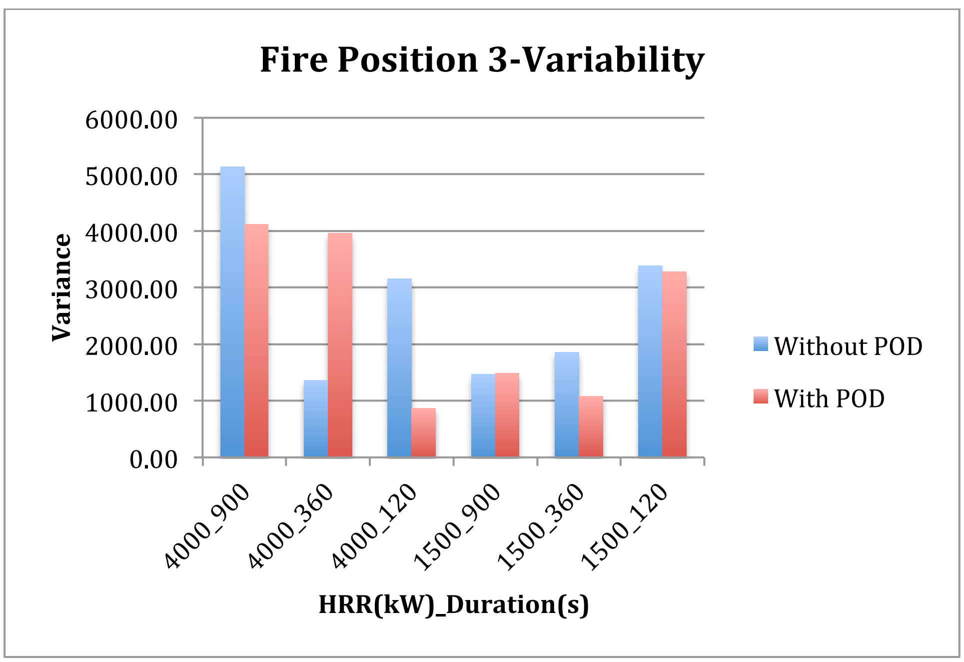


Figure G-3: Fire Position 3 Variability

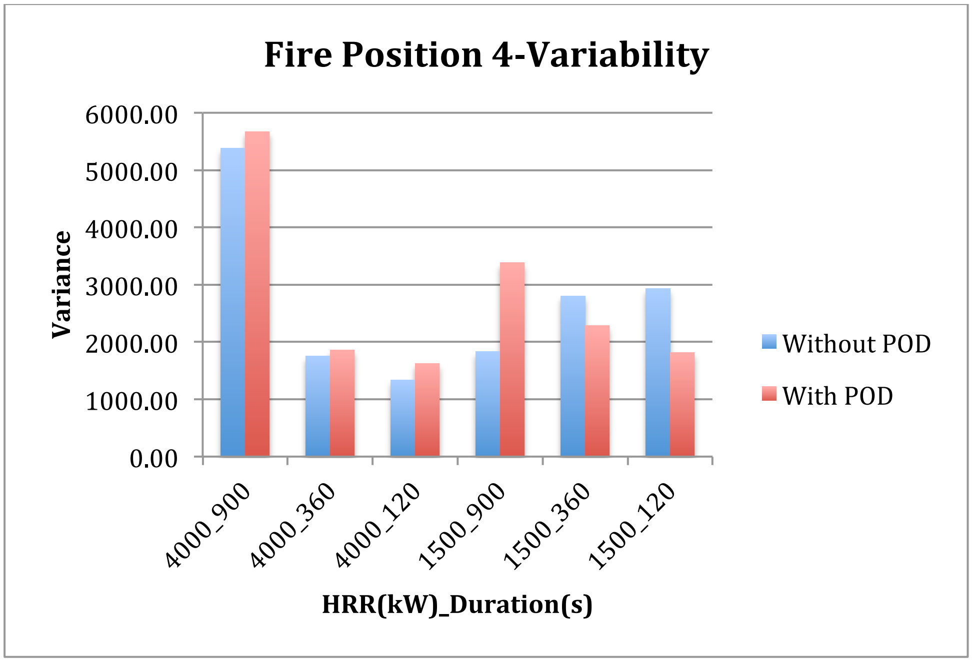


Figure G-4: Fire Position 4 Variability

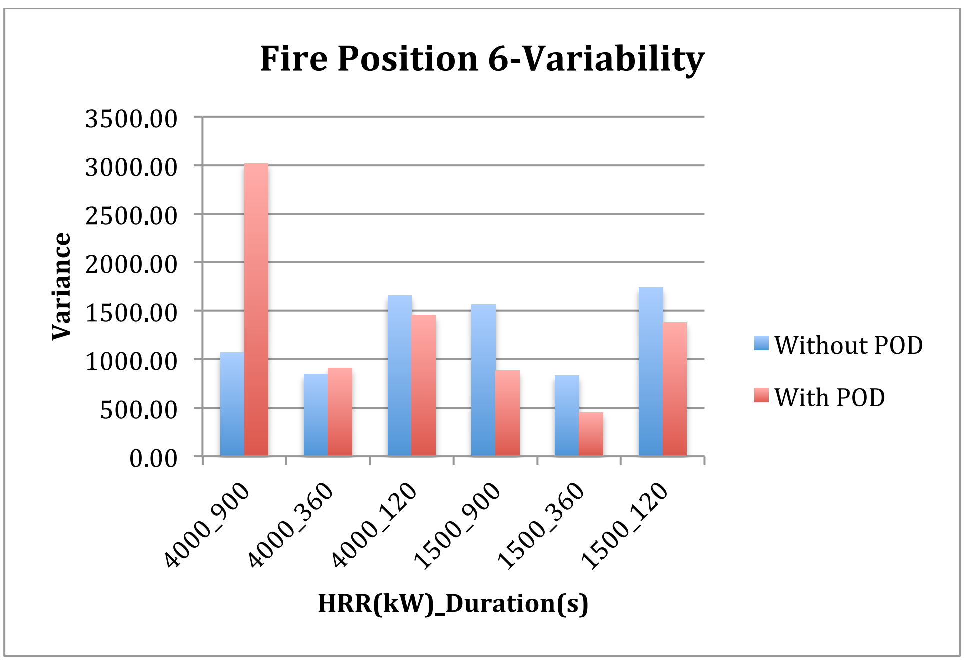


Figure G-5: Fire Position 6-Variability

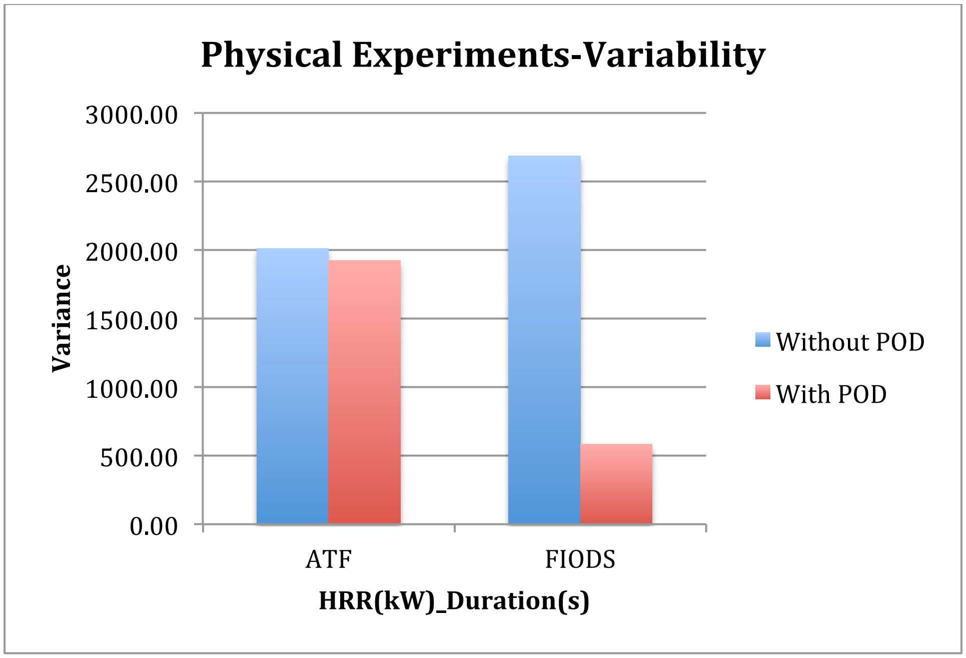


Figure G-6: Physical Experiments-Variability

As the general trend indicated that the greatest variability was identified with the highest heat release rate and longest duration simulations, it was necessary to evaluate the results of these simulations more closely. The highest HRR and longest duration simulations were the 4000kW fires at 360 seconds and 900 seconds, and the 1500kW fire at 900 seconds. Specifically, it was important to evaluate the influence of the POD on these more difficult scenarios. Out of these simulations, 7 performed better with the POD (47%), 1 performed at the same level (6%), and 7 had greater variability (47%) (Table G-3, Figure G-7).

Table G-3: Influence of the POD on the highest HRR and longest duration simulations

	Number of Scenarios	Total scenarios	%
Decreasing variability w/POD	7	15	47
Increasing variability w/POD	7	15	47
No change in variability	1	15	6

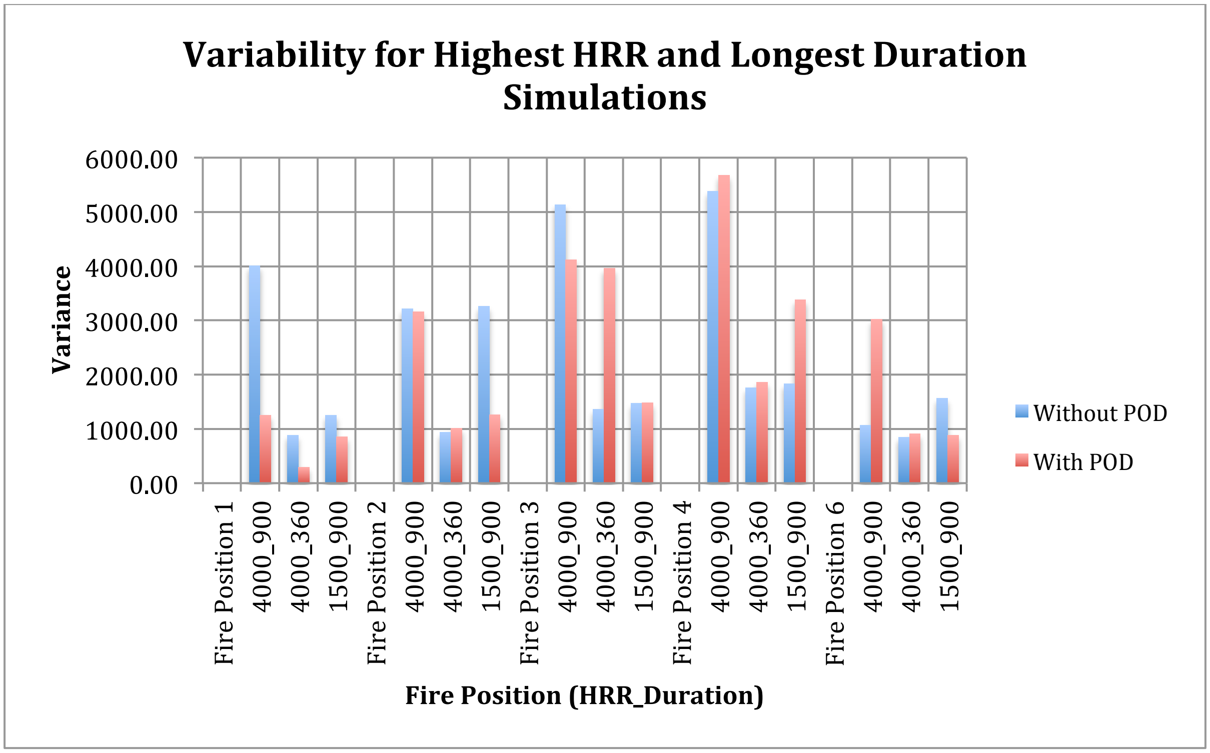


Figure G-7: Variability for the highest HRR and longest duration simulations

Another method to evaluate the reliability of the POD was accomplished through plotting each answer set as a scatter plot, finding the centroid of that answer set, calculating the distance from that centroid to all answers, and then calculating the 95% confidence interval of the answer set. The centroid, or the geometric center of the data, was calculated for the answer sets for each scenario without the POD and with the POD. The distance between each X- and Y-coordinate selected by a participant as the center point of his or her area of origin was then calculated from this centroid coordinate. From this, a 95% confidence interval distance was calculated and used as the diameter of an ellipse that centered on the centroid for the answer set. If the diameter of the ellipse is smaller when using the POD, then it can be concluded that the answers were more consistent and therefore more reliable with the use of the POD. A graphical comparison of the answer set for each scenario was plotted for those that used the POD compared to those that did not (Figures G-8 through G-39). The 95% confidence interval was calculated from the following equation:

$$\mu + 1.96\left(\frac{\sigma}{\sqrt{n}}\right)$$

Where: μ = mean
σ = standard deviation
n = sample size (number of participants)

The distance between two coordinate points was calculated from the distance equation:

$$d = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$

The coordinate for the true point of origin was also plotted. The closer the centroid was to the true point of origin, the more accurate the answer set was to the true origin, which indicates validity of the POD. The plots below illustrate two data sets (1) without POD and (2) with POD, two ellipses each with a diameter based on the 95% confidence interval for the distances for each data set, centroid for both data sets, and the true center point. Evaluating the diameter of the ellipses can assess reliability. The dashed line ellipse illustrates the 95% confidence interval distance diameter for the answer set without the POD, while the solid line ellipse illustrates the 95% confidence interval distance diameter for the answer set with the POD. The blue dots represent the answers from participants without the POD, green asterisks represent the answers from participants with the POD, the blue square indicates the centroid of the data set without POD, the black square indicates the centroid of the data set with the POD, and the red square indicates the true center point for the area of origin (Figures 22-53). As confirmation to the variance results from above, 21 of 32 (66%) scenarios had a smaller diameter ellipse for the answers using the POD. A total of 24 of the 32 (75%) scenarios had their centroid closer to the true center when using the POD. Of those 11 scenarios where the POD results were not as consistent (i.e. larger diameter and larger variance), the centroid was closer to the true center with using the POD. An increase in reliability has been identified when using the POD. Also, the first validity test (i.e. centroid closer to the true center) established that when using the POD, participants were 75% more likely to be closer to the true center than when not using the POD.

The greatest variability again was observed with the higher heat release rate simulations at the longer durations. As mentioned previously, this was expected based on previous review of the literature. Interestingly, four of the eleven that demonstrated greater variability was found with fire position 4 (near wall fire).

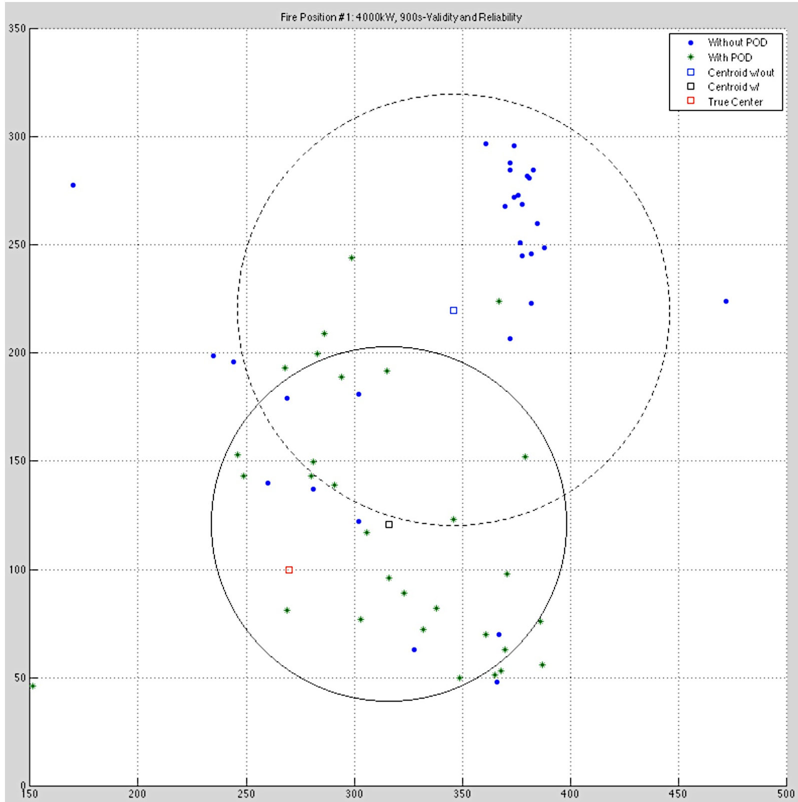


Figure G-8: Fire Position #1 (4000kW / 900s) Scatterplot of Answers

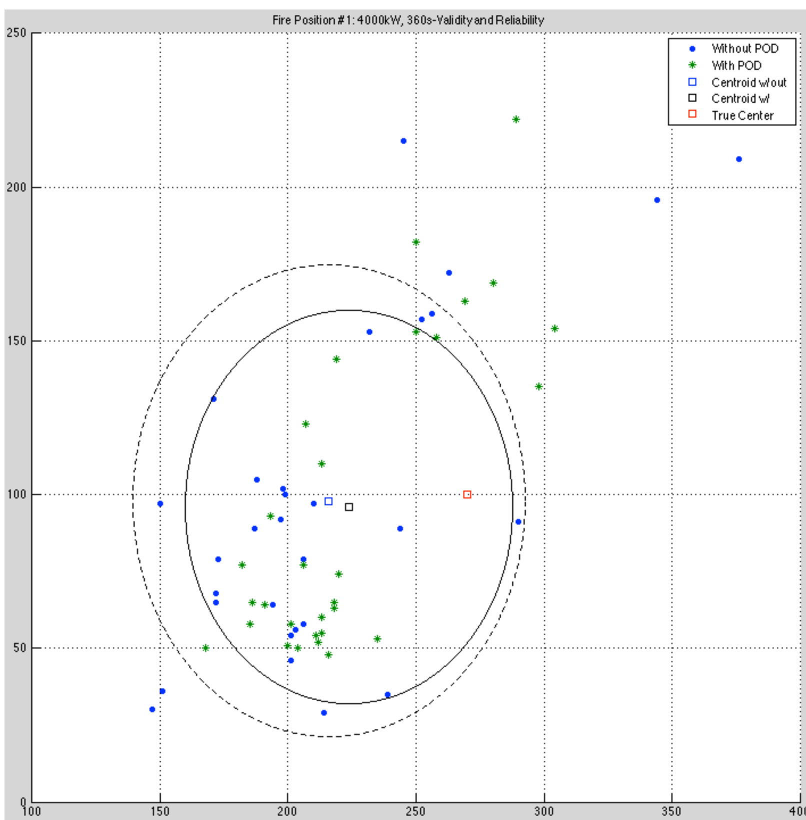


Figure G-9: Fire Position #1 (4000kW / 360s) Scatterplot of Answers

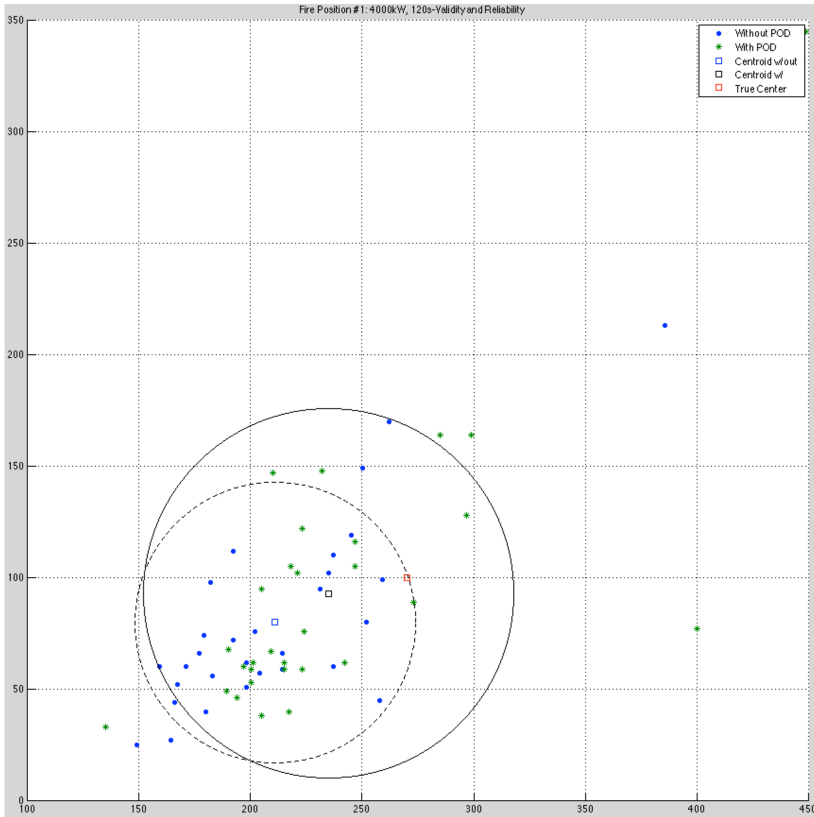


Figure G-10: Fire Position #1 (4000kW / 120s) Scatterplot of Answers

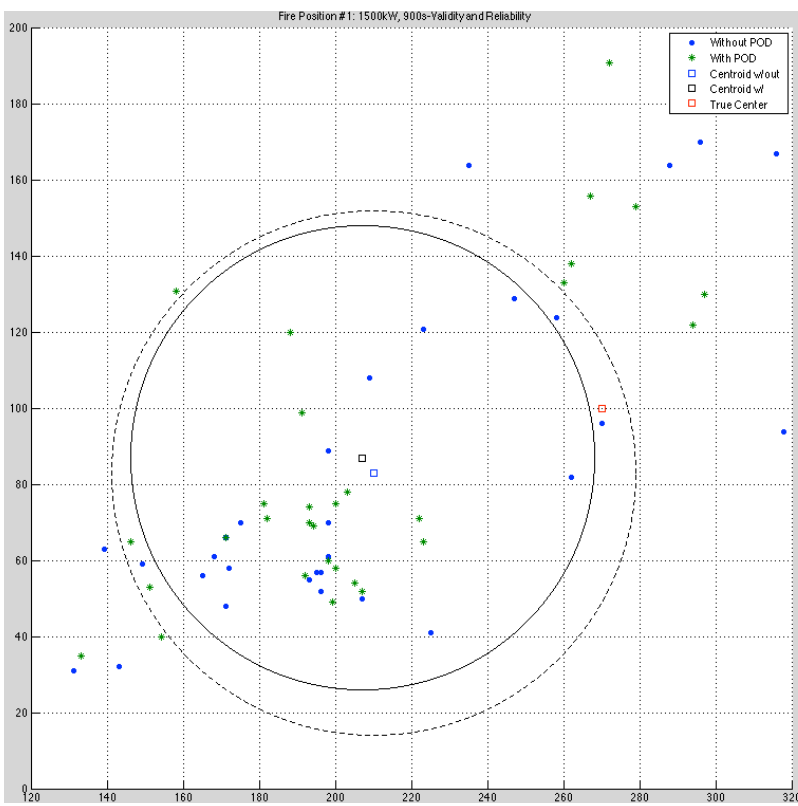


Figure G-11: Fire Position #1 (1500kW / 900s) Scatterplot of Answers

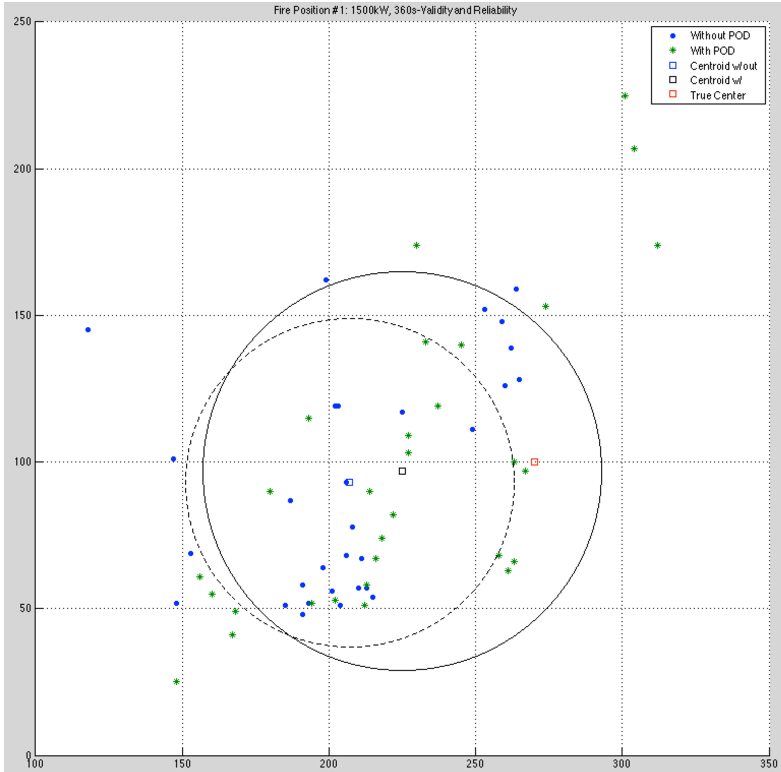


Figure G-12: Fire Position #1 (1500kW / 360s) Scatterplot of Answers

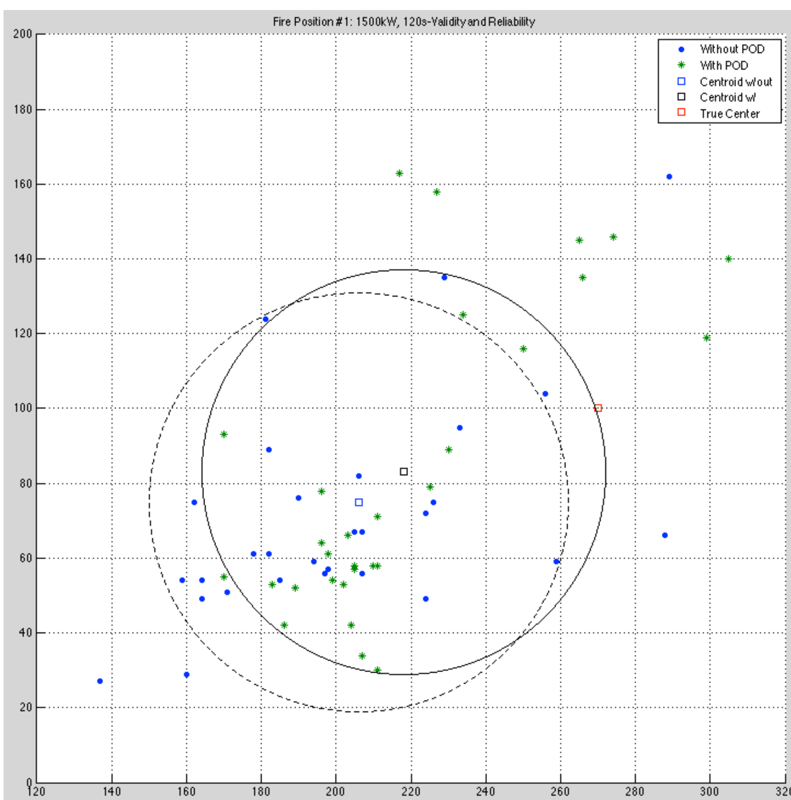


Figure G-13: Fire Position #1 (1500kW / 120s) Scatterplot of Answers

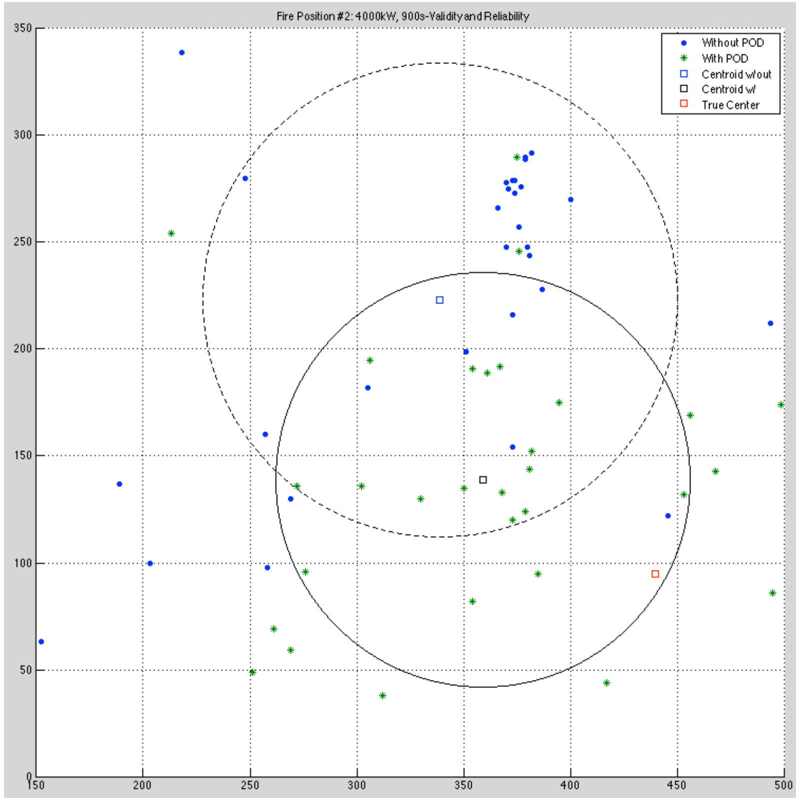


Figure G-14: Fire Position #2 (4000kW / 900s) Scatterplot of Answers

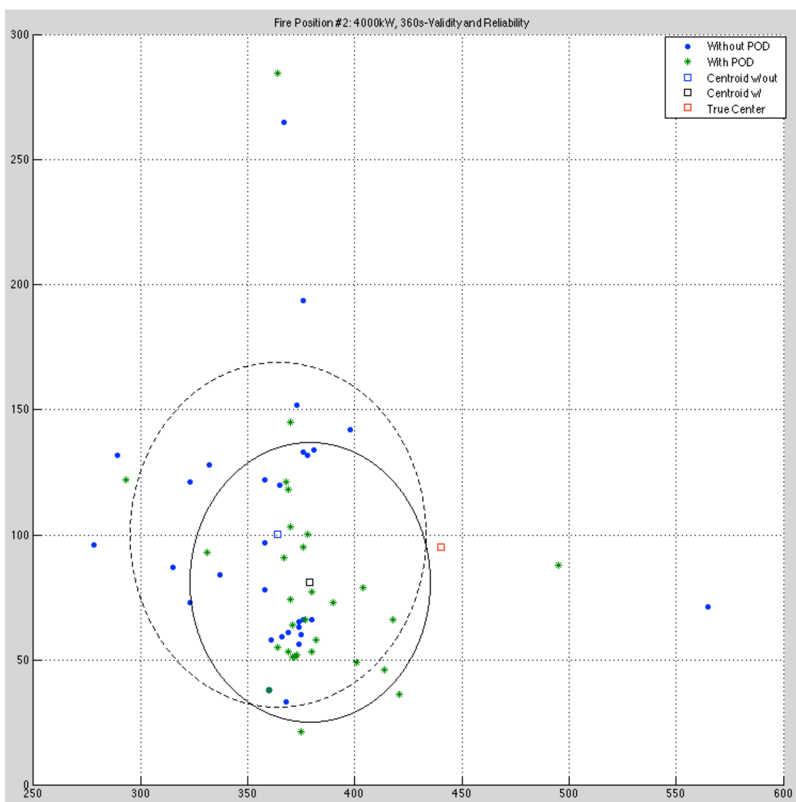


Figure G-15: Fire Position #2 (4000kW / 360s) Scatterplot of Answers

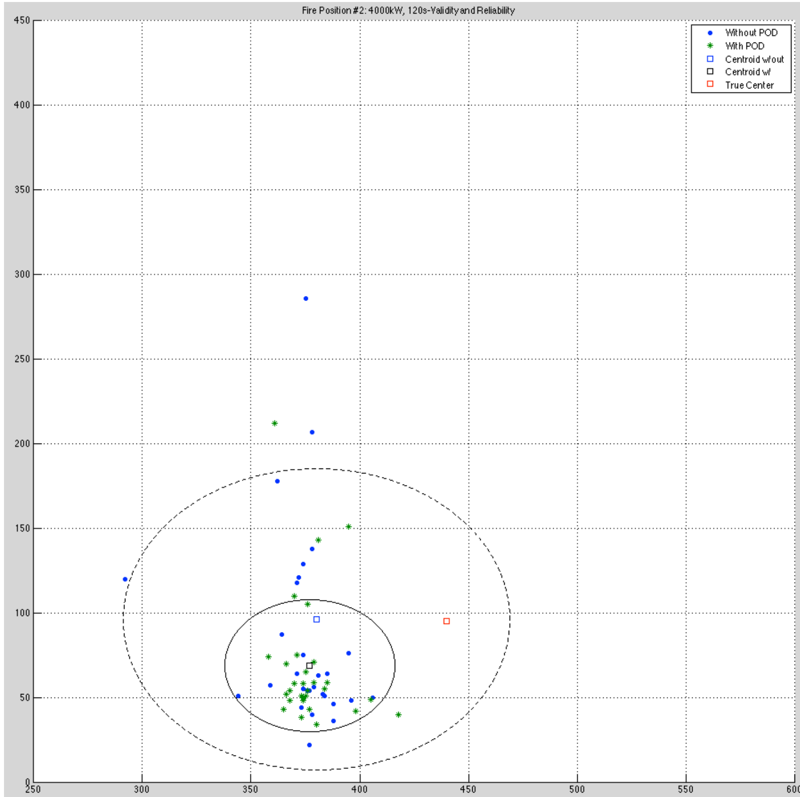


Figure G-16: Fire Position #2 (4000kW / 120s) Scatterplot of Answers

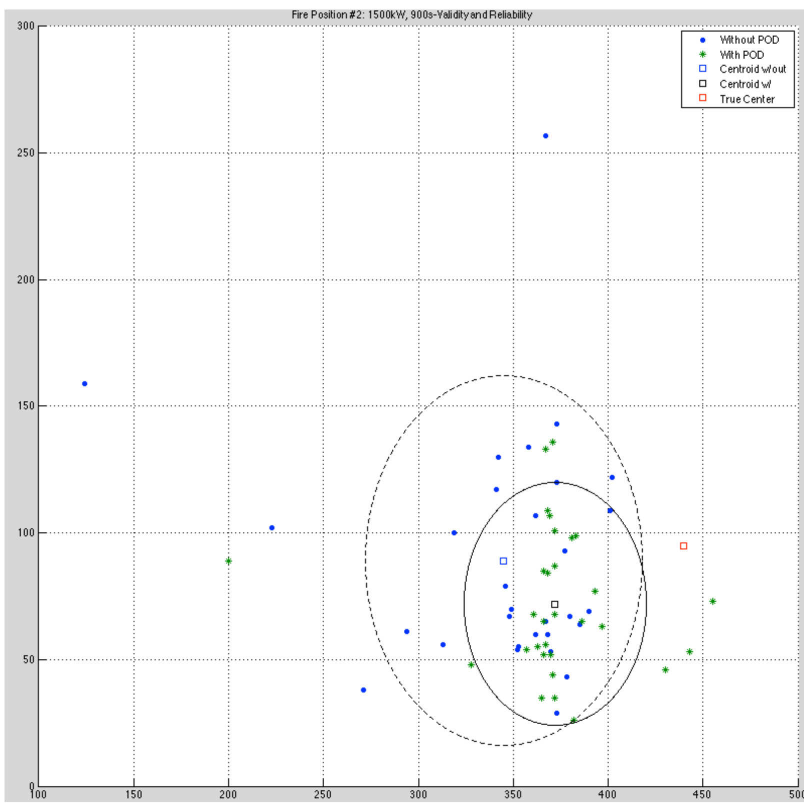


Figure G-17: Fire Position #2 (1500kW / 900s) Scatterplot of Answers

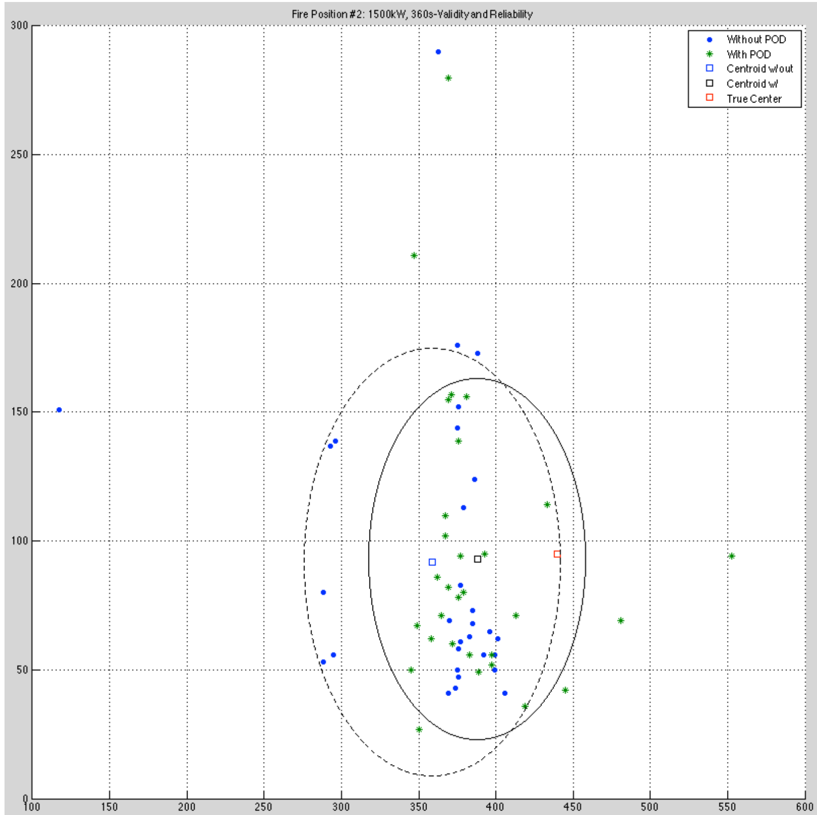


Figure G-18: Fire Position #2 (1500kW / 360s) Scatterplot of Answers

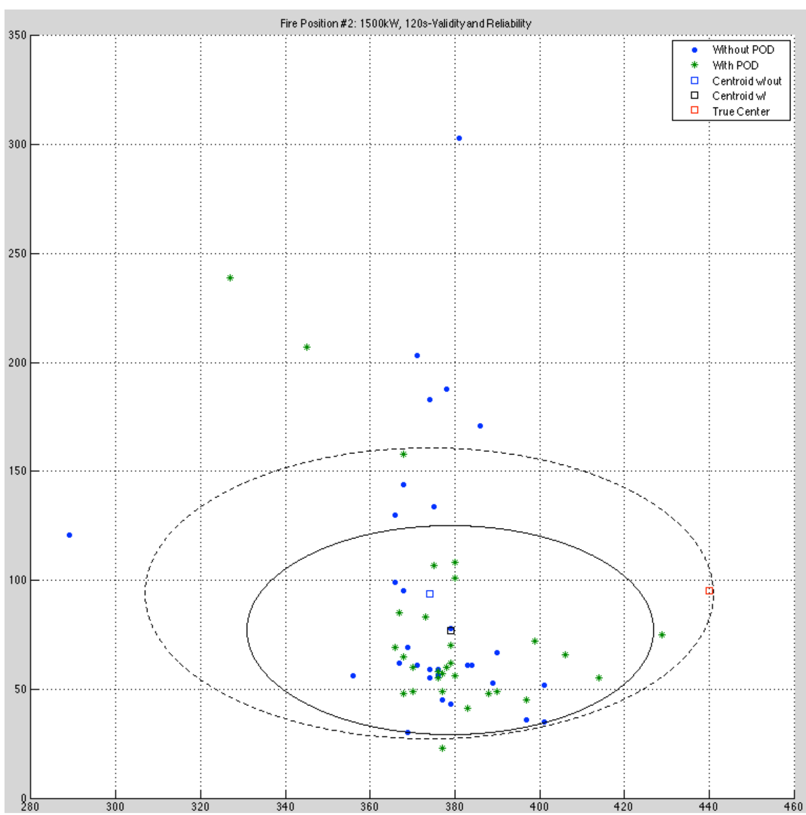


Figure G-19: Fire Position #2 (1500kW / 120s) Scatterplot of Answers

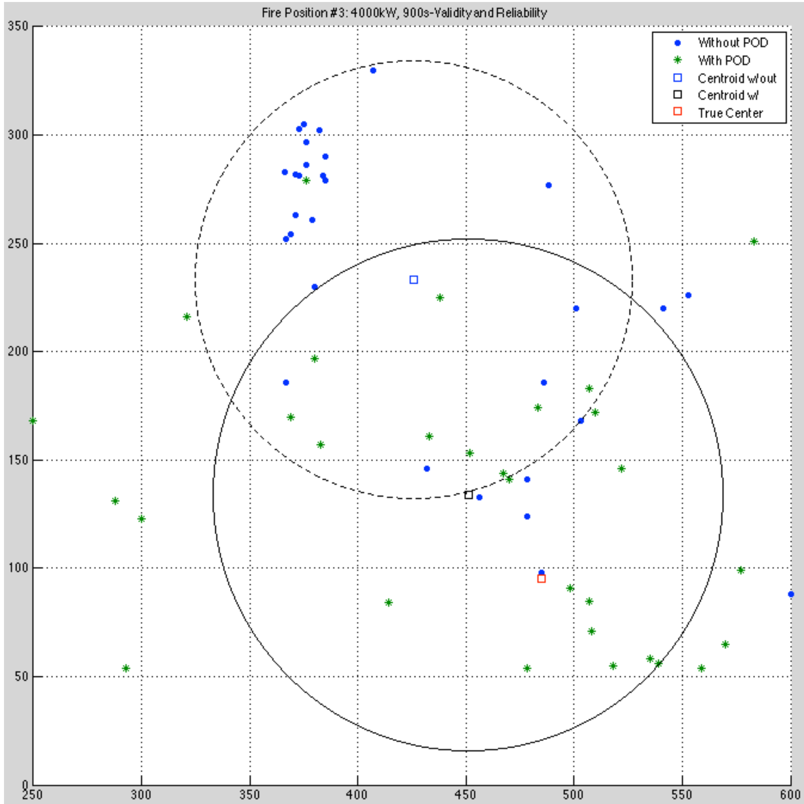


Figure G-20: Fire Position #3 (4000kW / 900s) Scatterplot of Answers

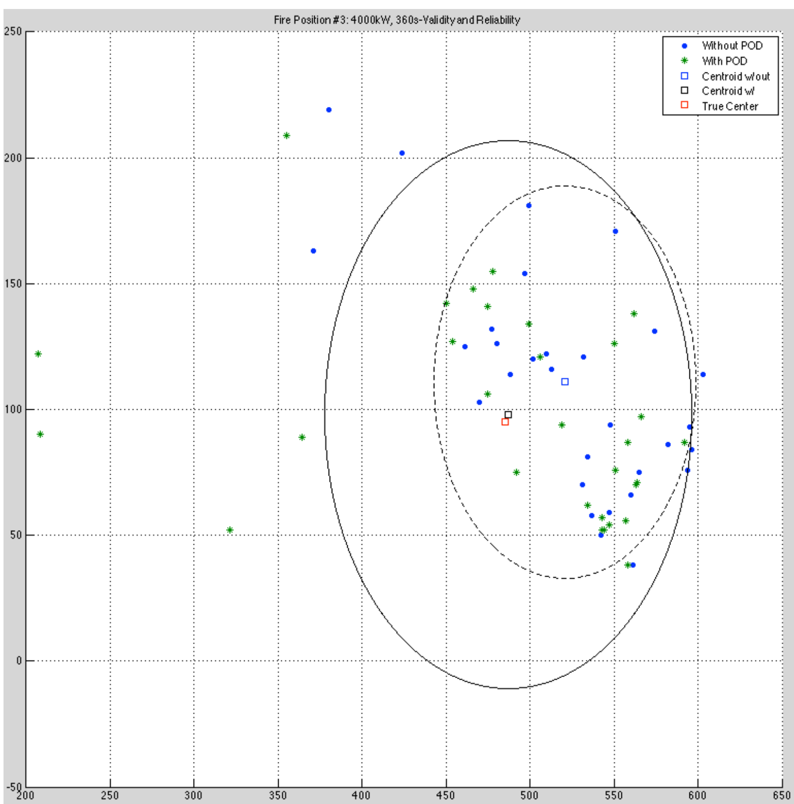


Figure G-21: Fire Position #3 (4000kW / 360s) Scatterplot of Answers

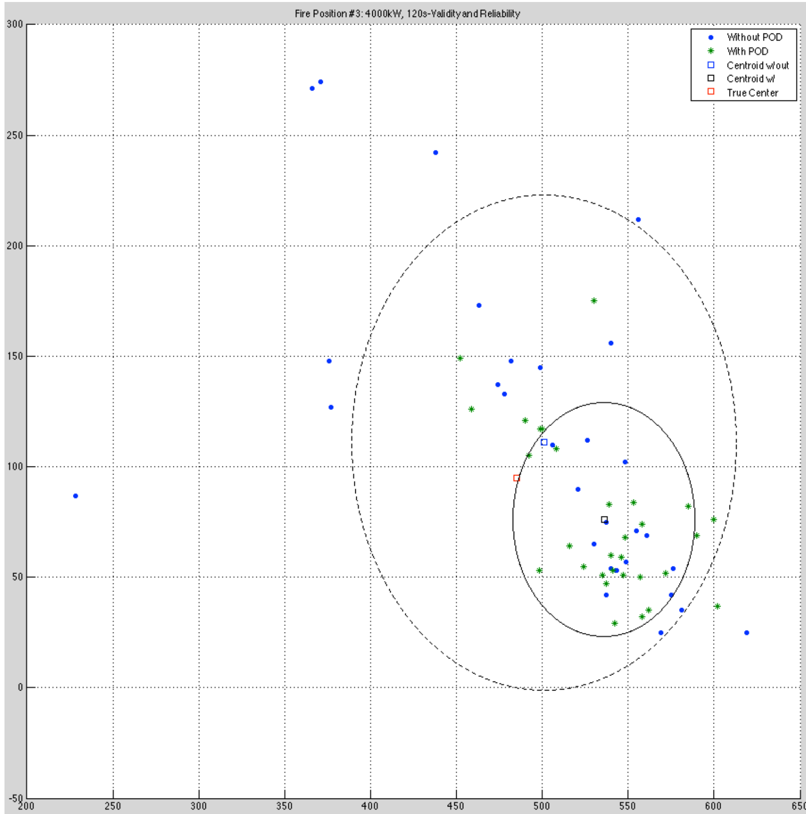


Figure G-22: Fire Position #3 (4000kW / 120s) Scatterplot of Answers

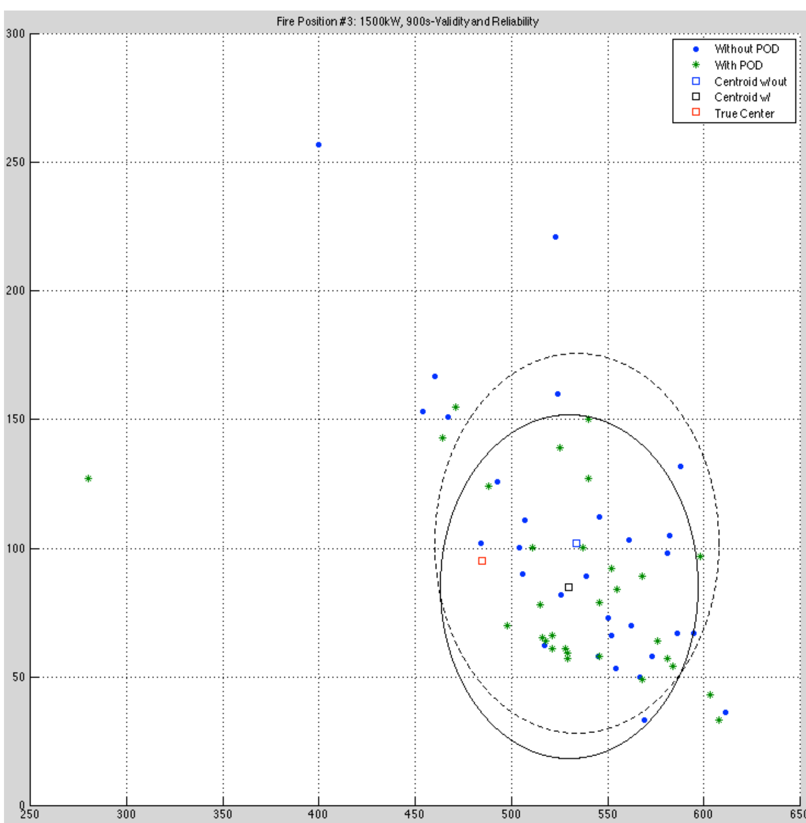


Figure G-23: Fire Position #3 (1500kW / 900s) Scatterplot of Answers

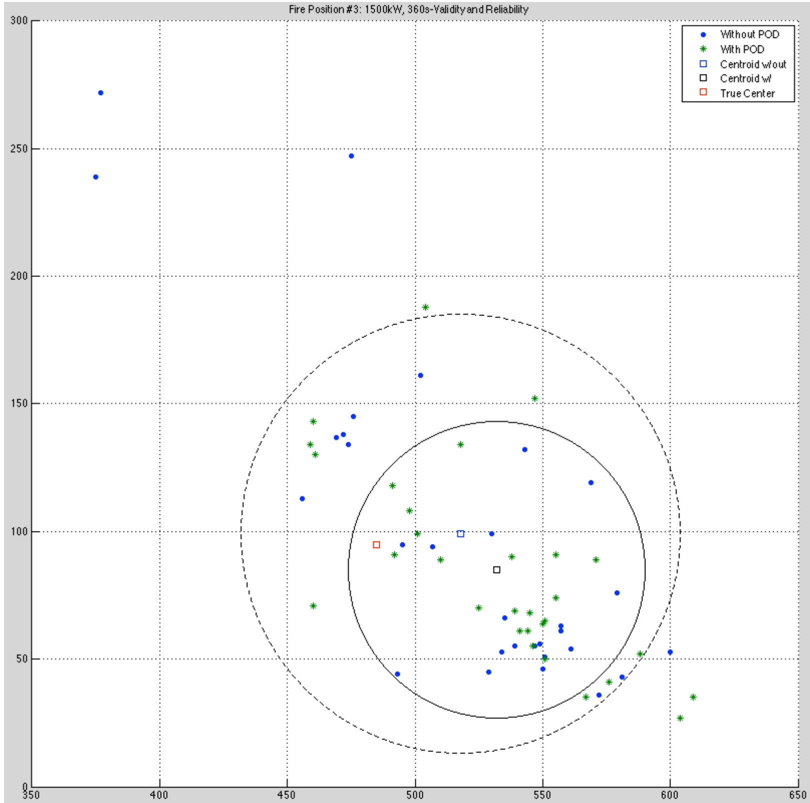


Figure G-24: Fire Position #3 (1500kW / 360s) Scatterplot of Answers

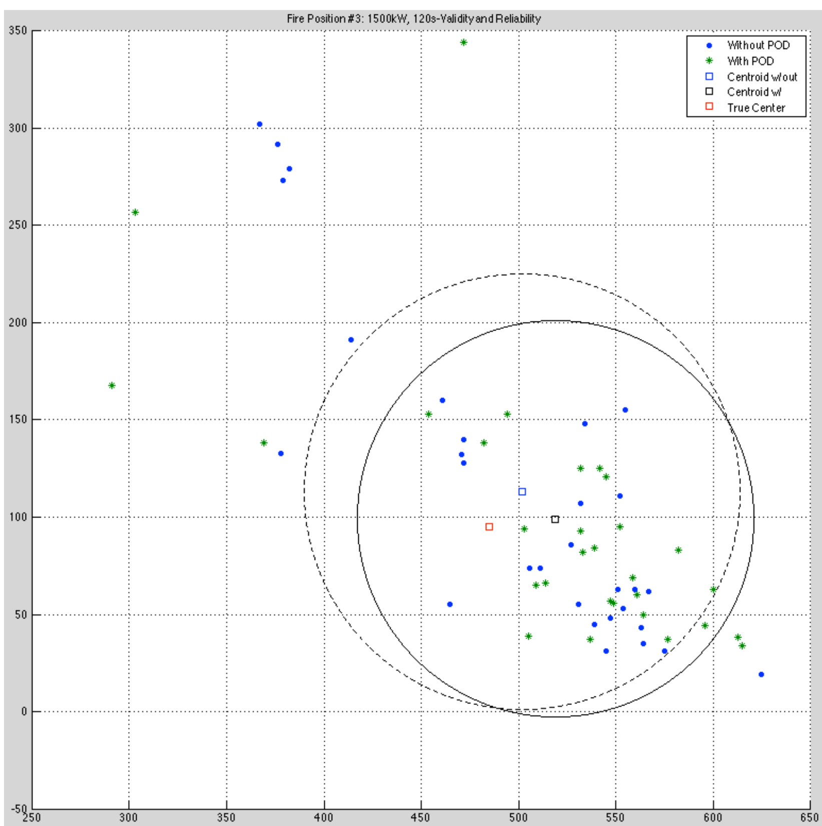


Figure G-25: Fire Position #3 (1500kW / 120s) Scatterplot of Answers

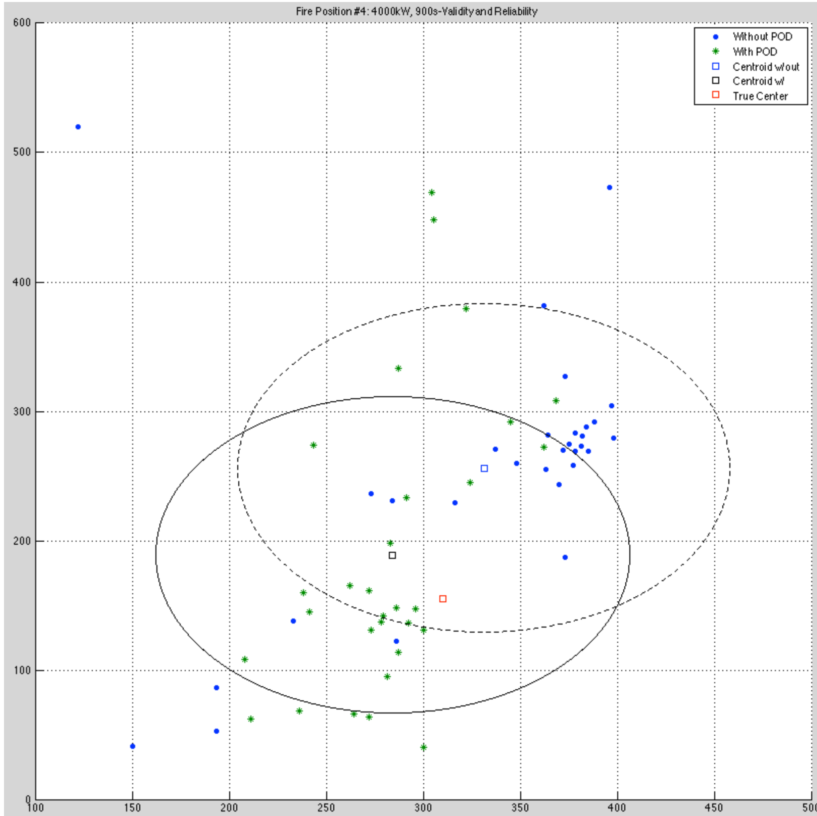


Figure G-26: Fire Position #4 (4000kW / 900s) Scatterplot of Answers

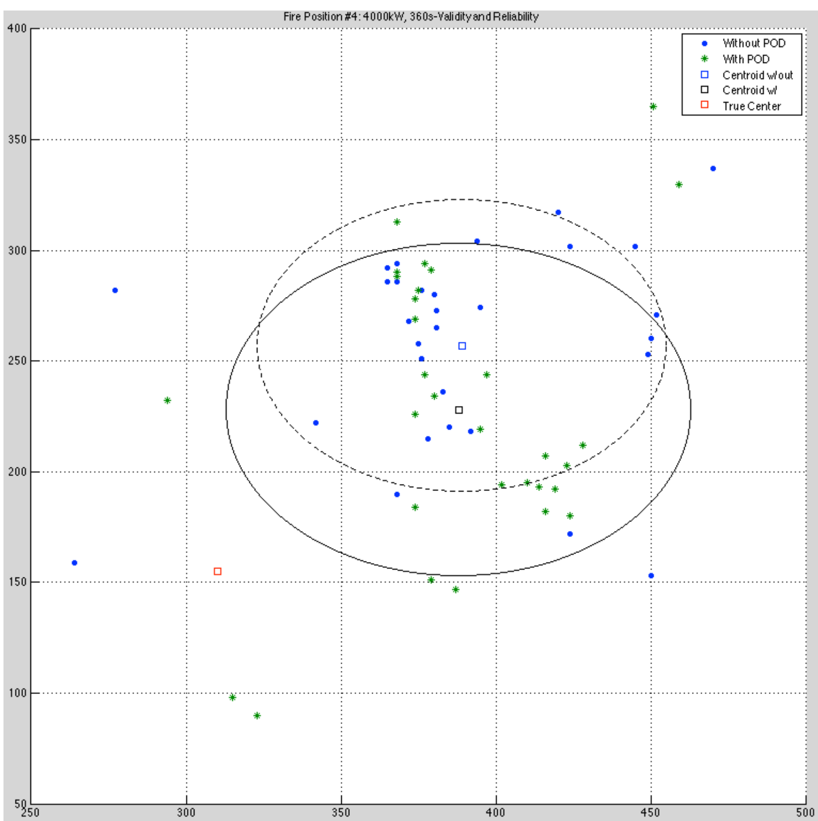


Figure G-27: Fire Position #4 (4000kW / 360s) Scatterplot of Answers

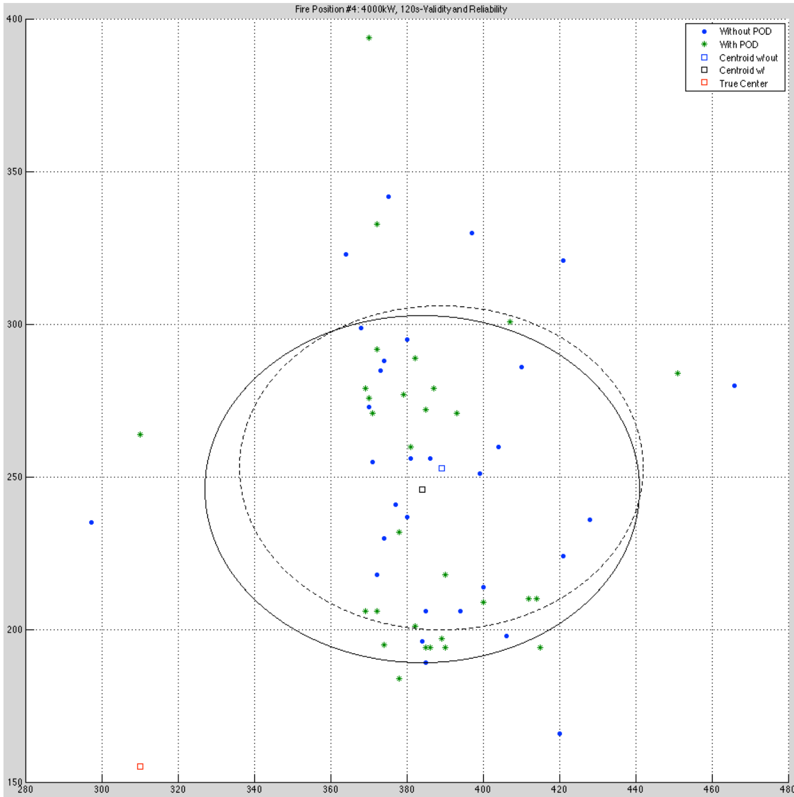


Figure G-28: Fire Position #4 (4000kW / 120s) Scatterplot of Answers

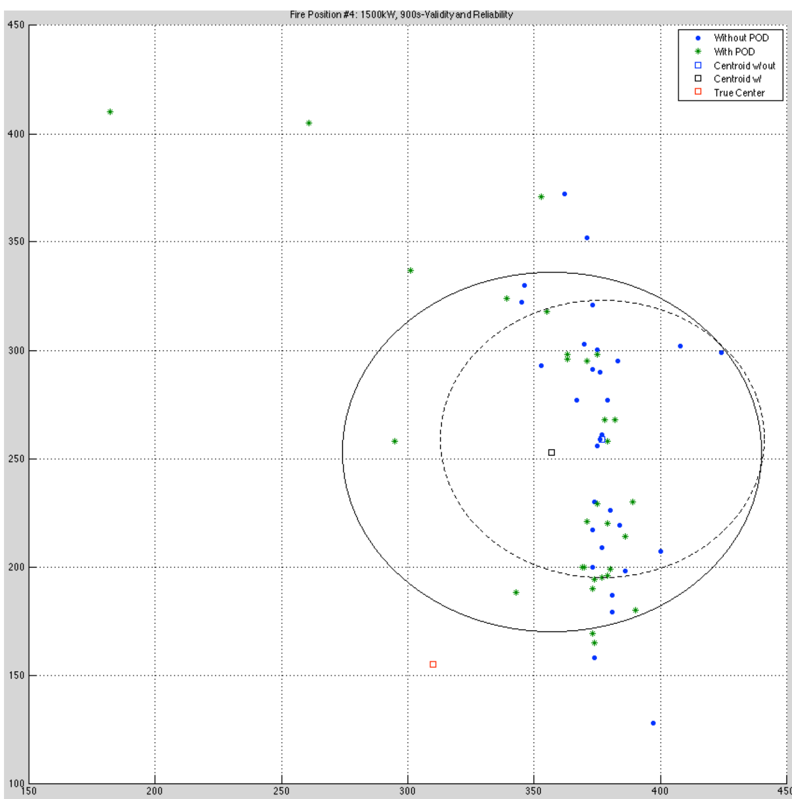


Figure G-29: Fire Position #4 (1500kW / 900s) Scatterplot of Answers

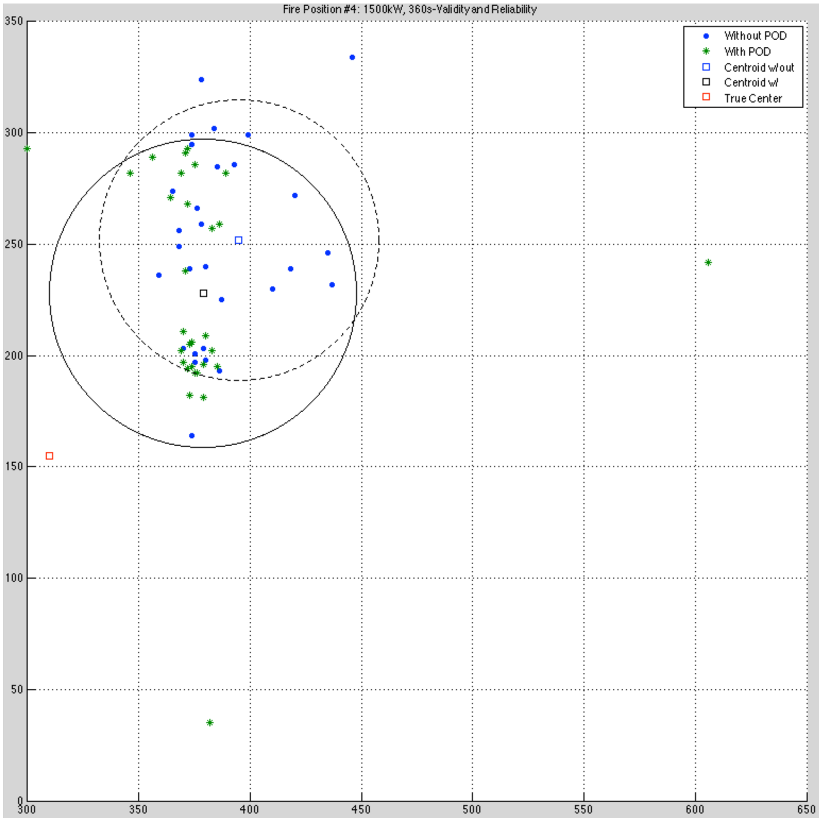


Figure G-30: Fire Position #4 (1500kW / 360s) Scatterplot of Answers

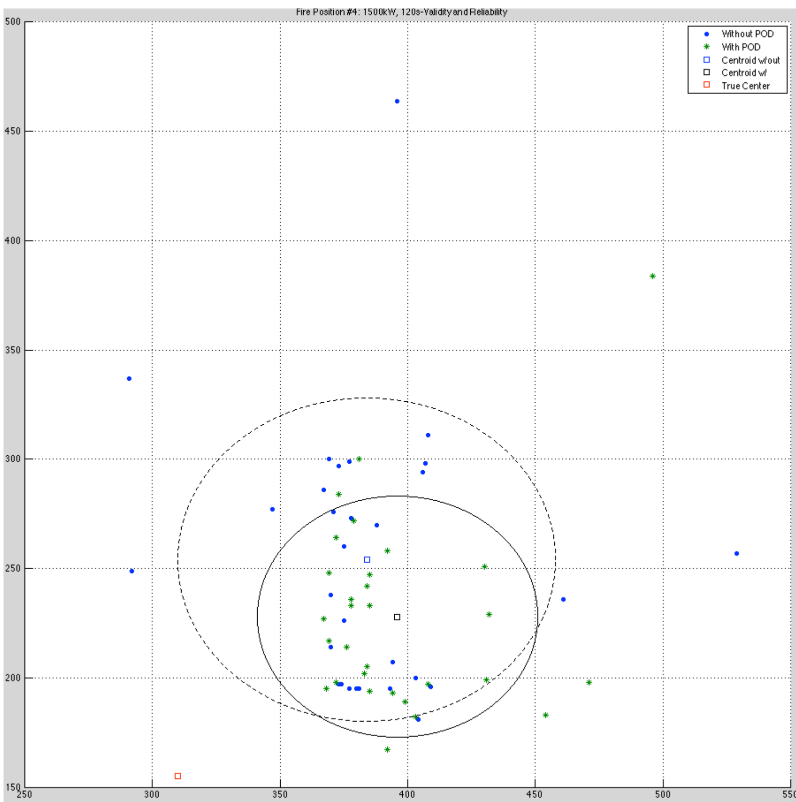


Figure G-31: Fire Position #4 (1500kW / 120s) Scatterplot of Answers

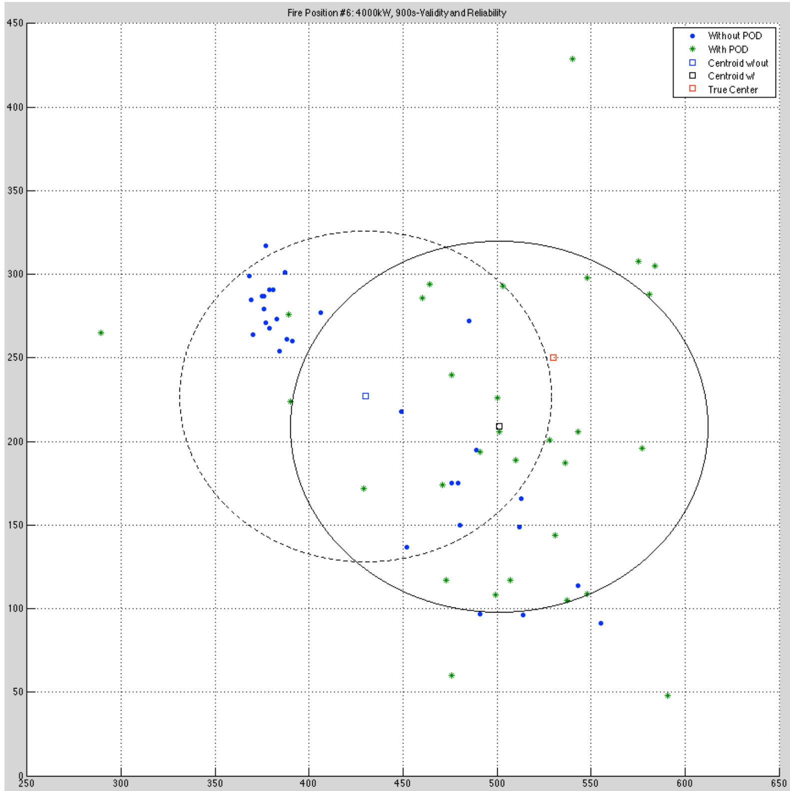


Figure G-32: Fire Position #6 (4000kW / 900s) Scatterplot of Answers

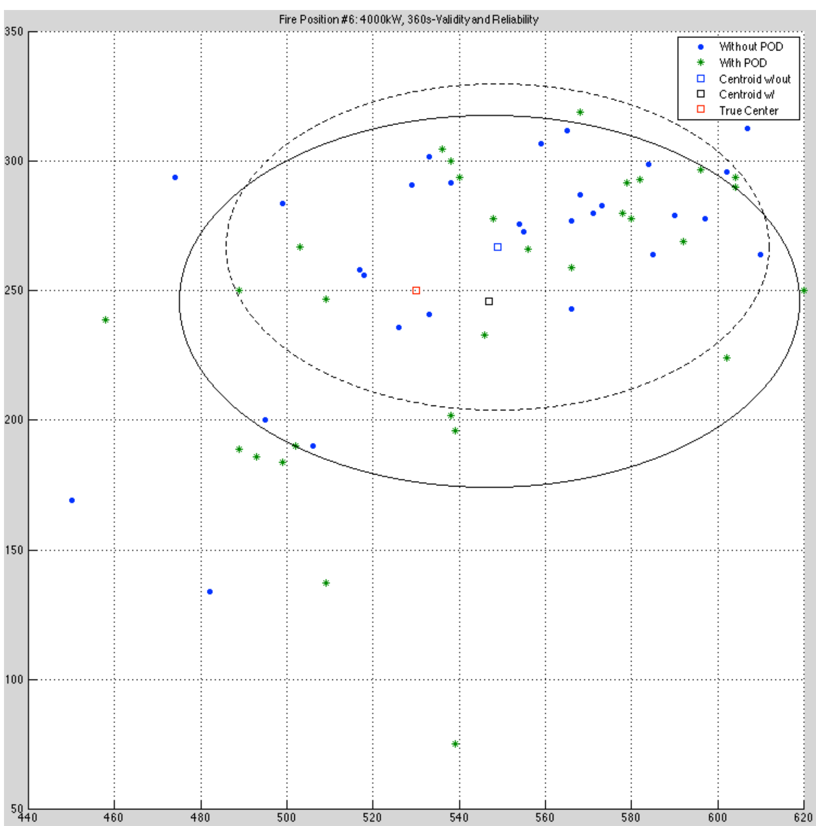


Figure G-33: Fire Position #6 (4000kW / 360s) Scatterplot of Answers

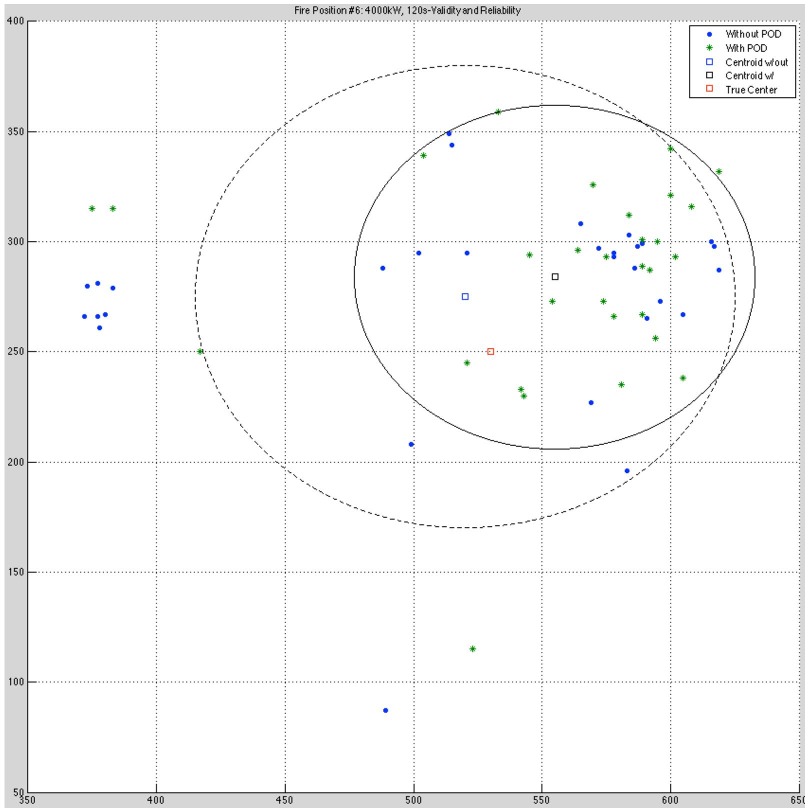


Figure G-34: Fire Position #6 (4000kW / 120s) Scatterplot of Answers

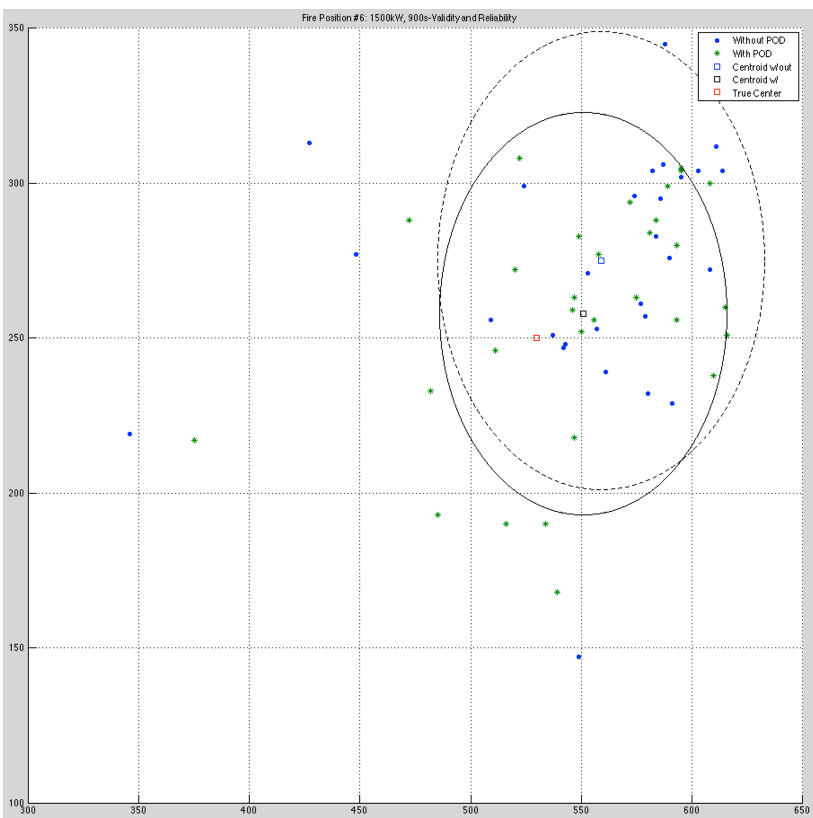


Figure G-35: Fire Position #6 (1500kW / 900s) Scatterplot of Answers

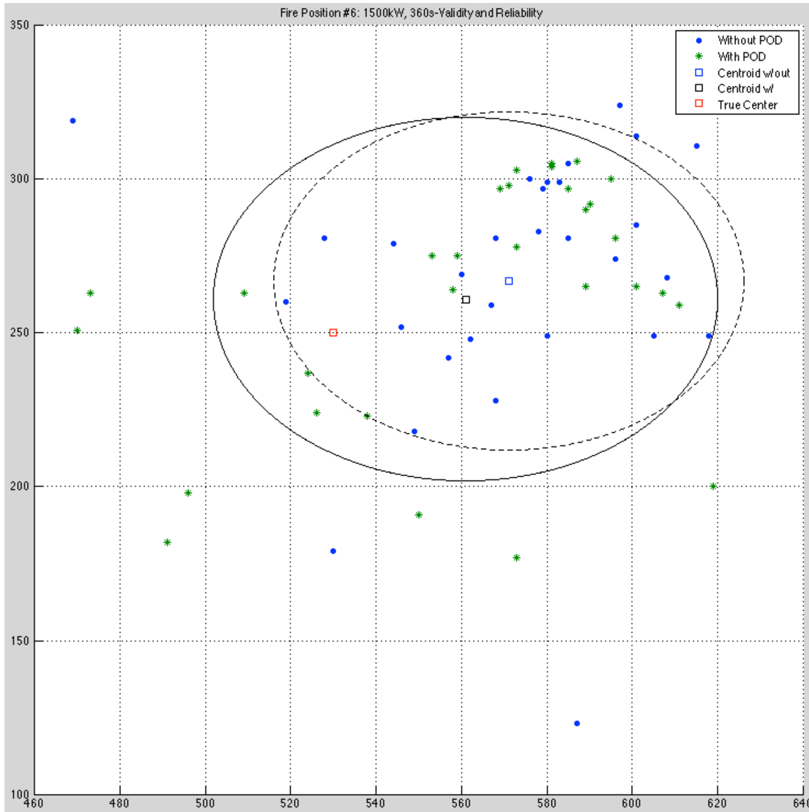


Figure G-36: Fire Position #6 (1500kW / 360s) Scatterplot of Answers

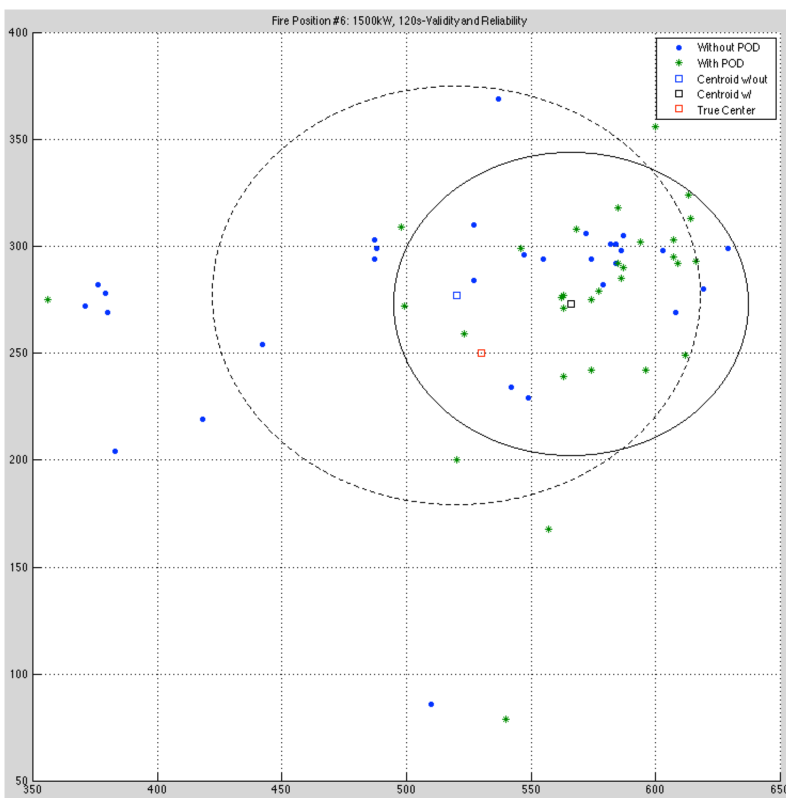


Figure G-37: Fire Position #6 (1500kW / 120s) Scatterplot of Answers

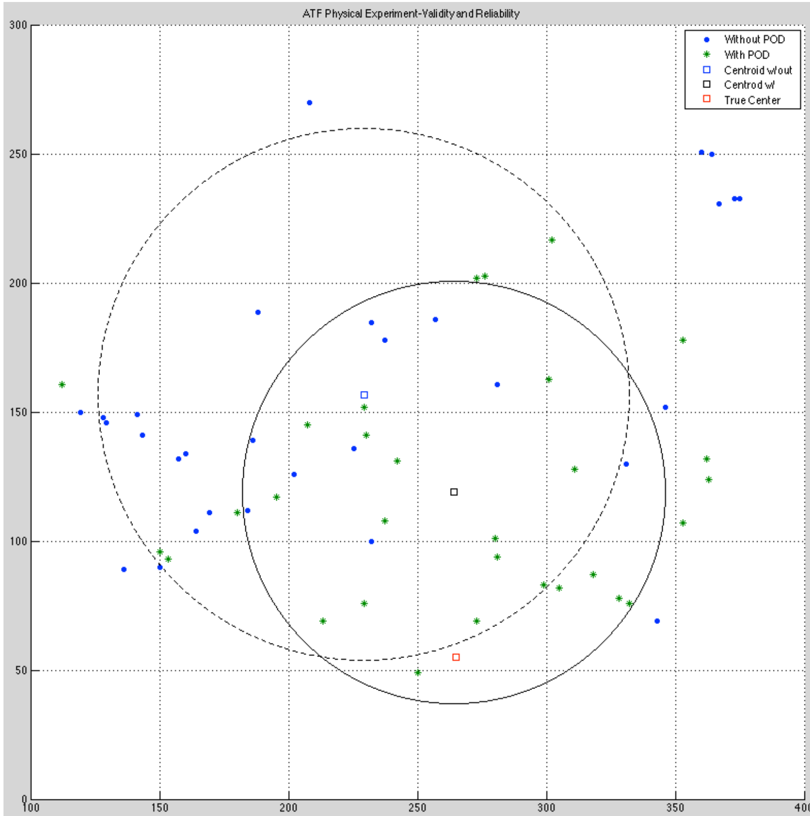


Figure G-38: ATF Physical Experiment Scatterplot of Answers

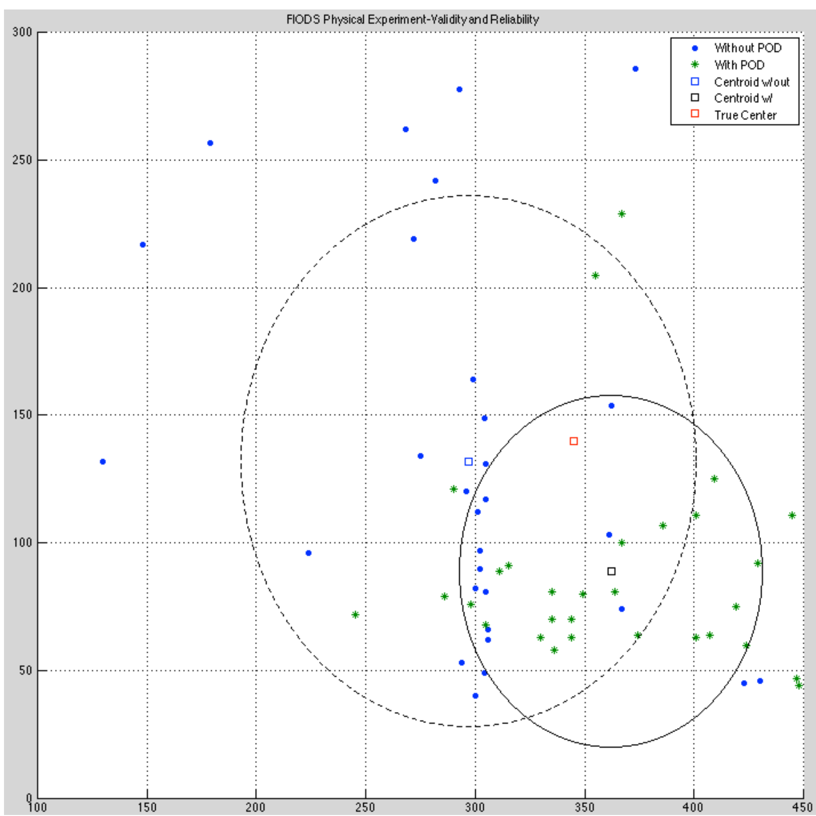


Figure G-39: FIODS Physical Experiment Scatterplot of Answers

G.2 Validation Charts

The validation studies were purposefully setup to evaluate the question for validity at varying levels. The first level was to evaluate whether the participants accurately identified the region that was the true area of origin. Next, the validation question evaluated whether or not the participants chose the correct region(s) reflected by the method. Finally, the validation question evaluated whether the center point identified by the participants were within an established area of origin.

G.2.1 Region Accuracy Charts

The first validation test evaluated which region(s) the participants selected as their area of origin. The participant was classified as accurate if they selected the region that reflected the region identified as the true origin. A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 19 out of 32 scenarios (59%), a decrease in accuracy when using the POD in only 6 out of 32 (19%), and no change in accuracy when using the POD in 7 out of 32 scenarios (22%) (Table G-4). None of the six scenarios that decreased in accuracy when using the POD were shown to be statistically significant. It was found that 6 out of the 19 scenarios (32%) that were shown to increase in accuracy when using the POD were statistically significant (Table G-4). Overall there is a statistically significant increase in accuracy rates for the true origin region when the POD was used (z=3.48, p=.001) (Table G-4). The nonparametric Wilcoxon test is a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed.

Table G-4: Validation Results – Comparison of Region Accuracy

OVERALL COMPARISON OF REGION ACCURACY RATES WITHOUT AND WITH THE POD			
	Number of scenarios	**Total scenarios**	**%**
Increasing accuracy with the method	19	32	59
No change in accuracy	7	32	22
Decreasing accuracy with method	6	32	19
STATISTICAL SIGNIFICANCE EVALUATION			
	# showing significant increase	**Total increasing scenarios**	**%**
Statistically significant increase (alpha =.05)	6	19	32
TEST FOR OVERALL SIGNIFICANCE			
	Without POD	**With POD**	
Mean (μ) accuracy rate	0.83	0.92	
Standard Deviation (σ)	0.12	0.14	
Median accuracy rates	0.78	0.97	
Independent samples t-test to compare means	t=2.74	p=.01	

Wilcoxon two-sample test to compare medians	z=3.48	p=0.001

To better evaluate any trends with the data, the region accuracy has been plotted by fire position. The general trend with the simulation data was a decrease in accuracy with the higher heat release rates and longer duration simulations (Figures G-40 through G-44). Fire position 4 (near wall fire) had the lowest accuracy rates of any of the simulations, however, the most significant increases in accuracy were demonstrated when the POD was used at this fire position. Both of the physical experiments had a statistically significant increase ($p<0.05$) in accuracy when using the POD (Figure G-45).

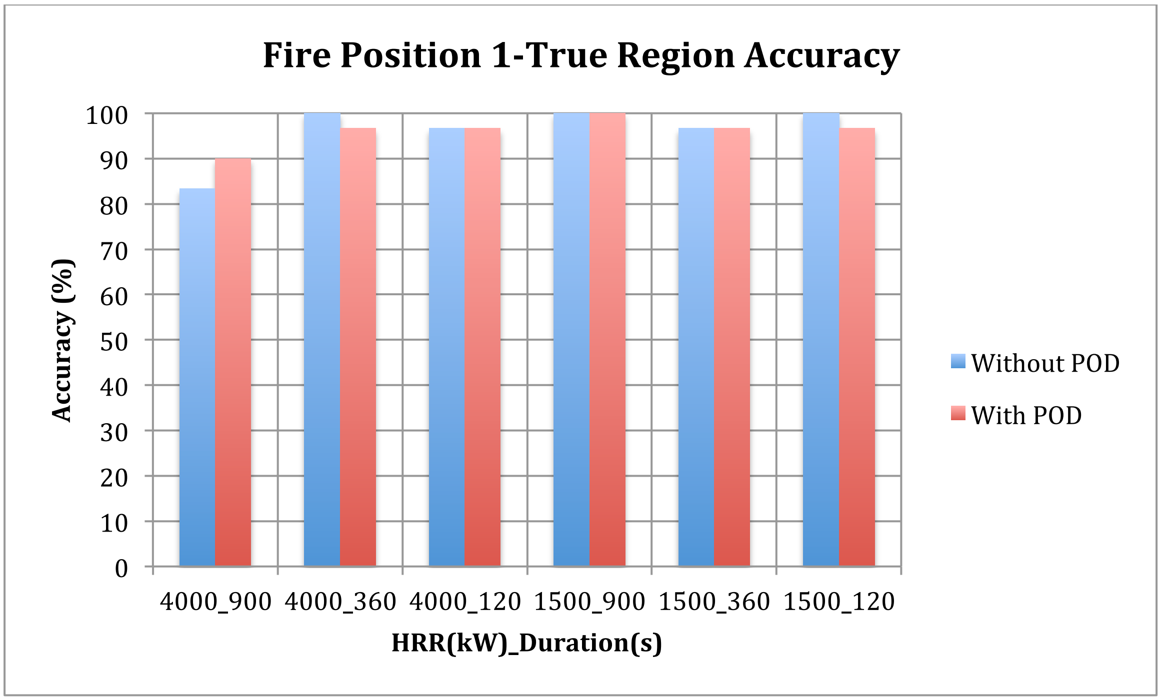


Figure G-40: Fire Position 1 Region Selection Accuracy

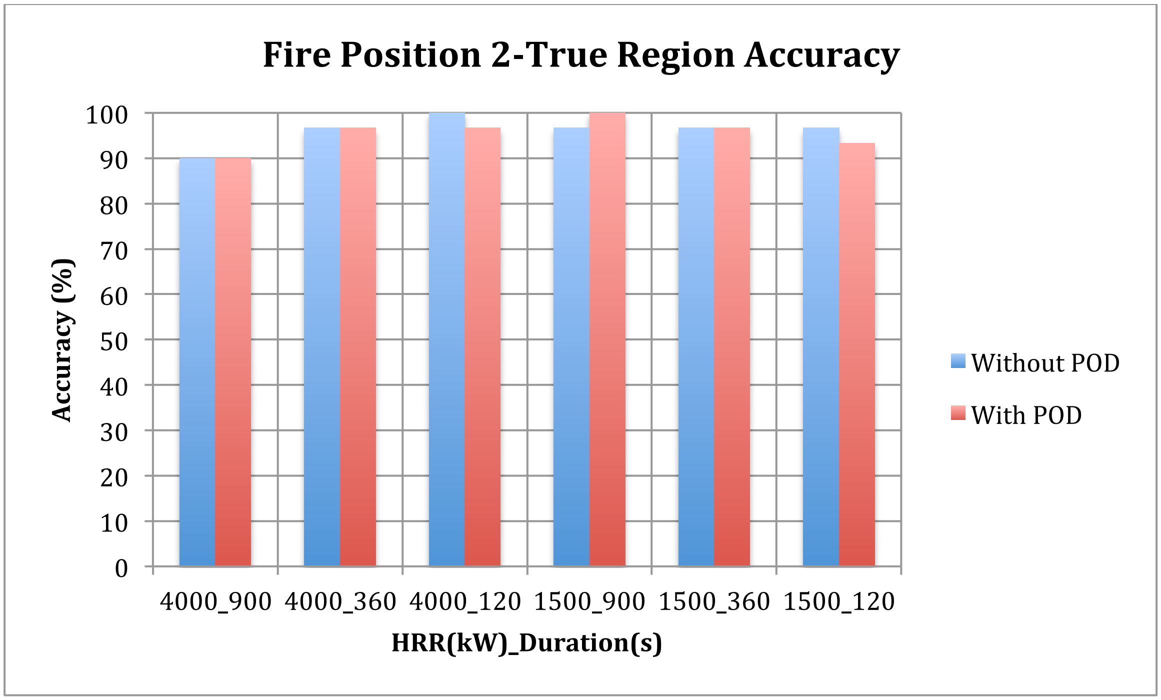


Figure G-41: Fire Position 2 Region Selection Accuracy

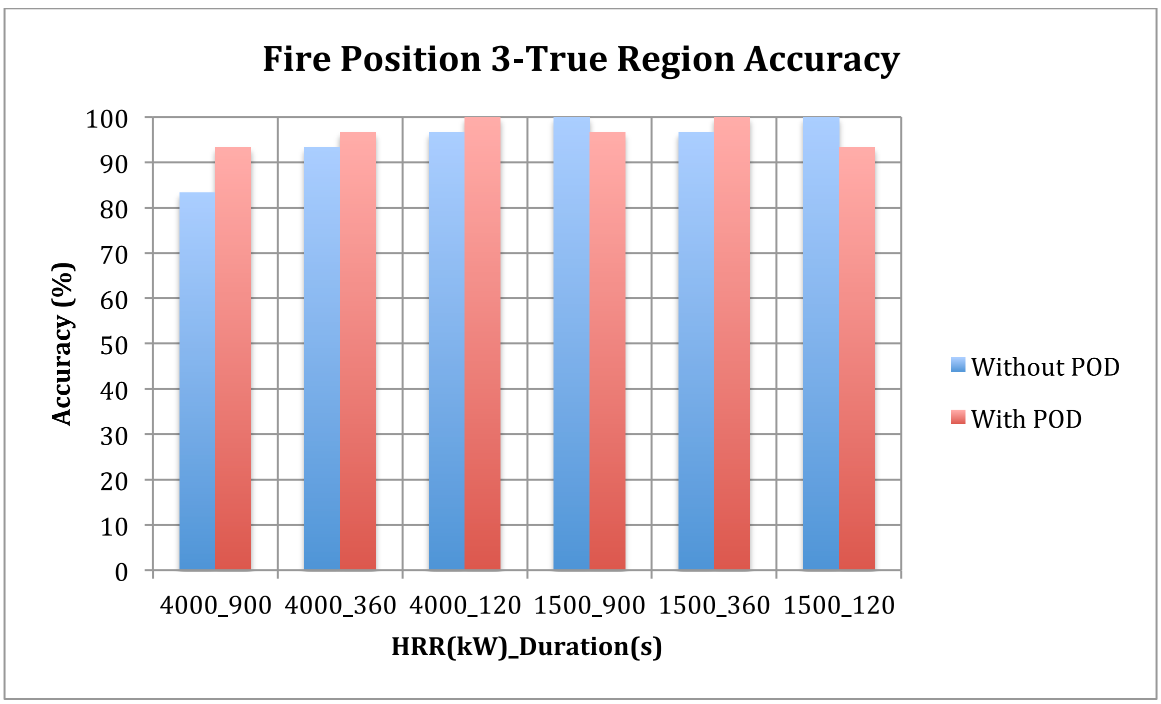


Figure G-42: Fire Position 3 Region Selection Accuracy

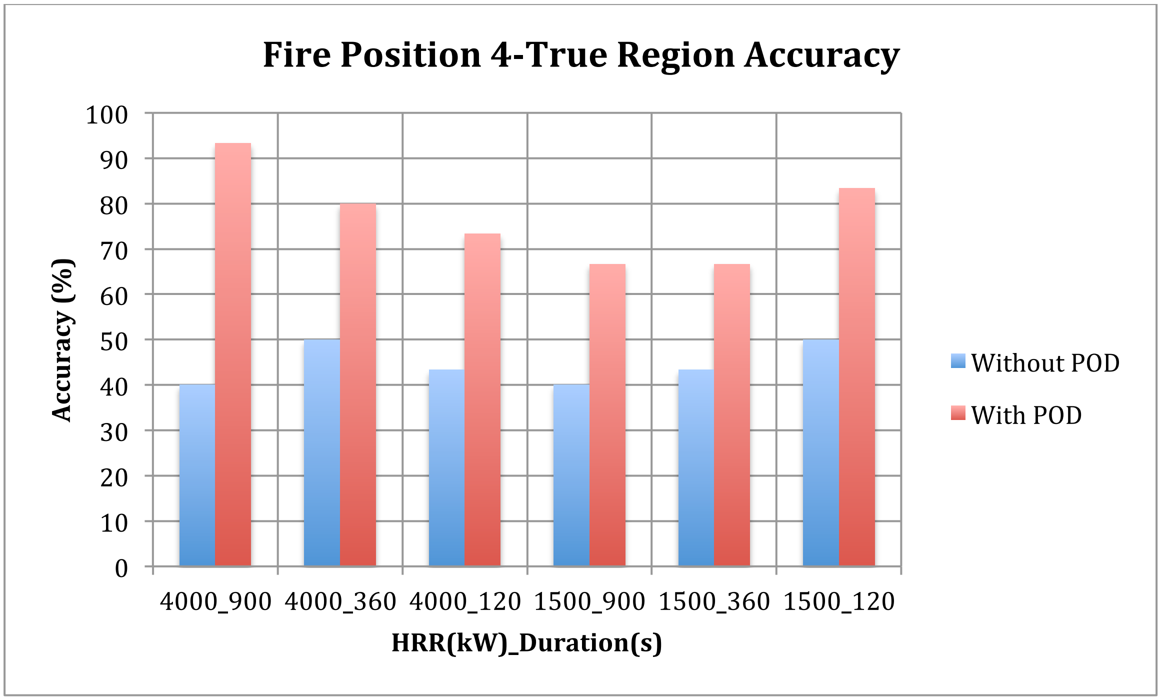


Figure G-43: Fire Position 4 Region Selection Accuracy

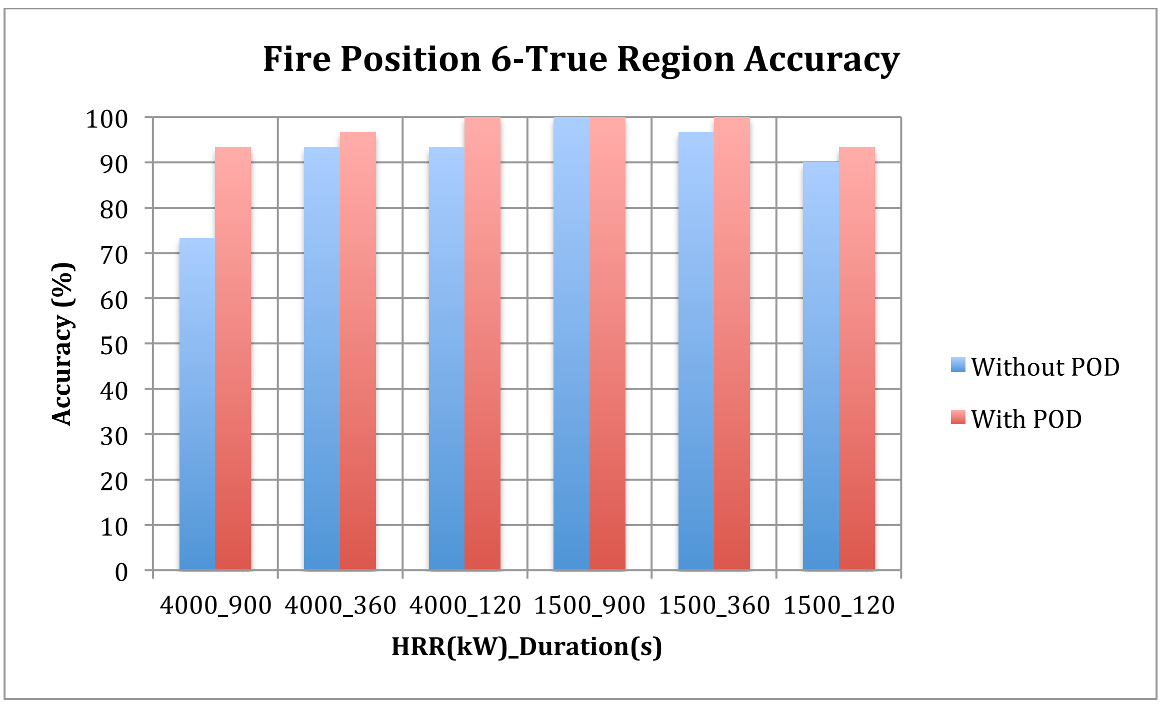


Figure G-44: Fire Position 6 Region Selection Accuracy

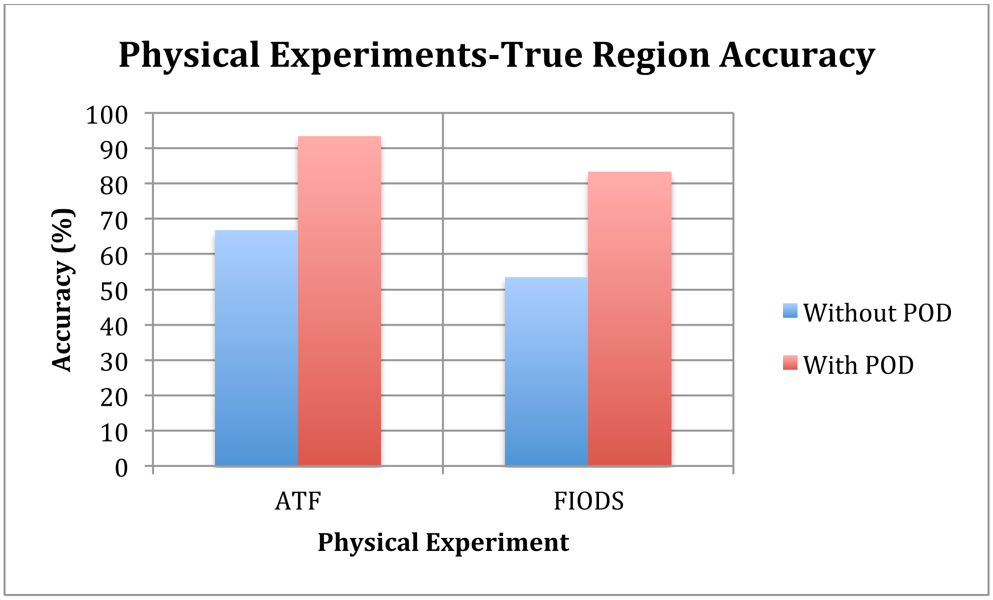


Figure G-45: Physical Experiments Region Selection Accuracy

As the general trend indicated that lower accuracy was identified with the highest heat release rate and longest duration simulations, it was necessary to evaluate the results of these simulations more closely. The highest HRR and longest duration simulations were the 4000kW fires at 360 seconds and 900 seconds, and the 1500kW fire at 900 seconds. Specifically, it was important to evaluate the influence of the POD on these more difficult scenarios. Out of these simulations 9 performed better with the POD (60%), 4 performed at the same level (27%), and 2 did slightly worse (13%) (Table G-5, Figure G-46).

Table G-5: Influence of the POD on the highest HRR and longest duration simulations

	Number of scenarios	Total scenarios	%
Increasing accuracy with the method	9	15	60
No change in accuracy	4	15	27
Decreasing accuracy with method	2	15	13

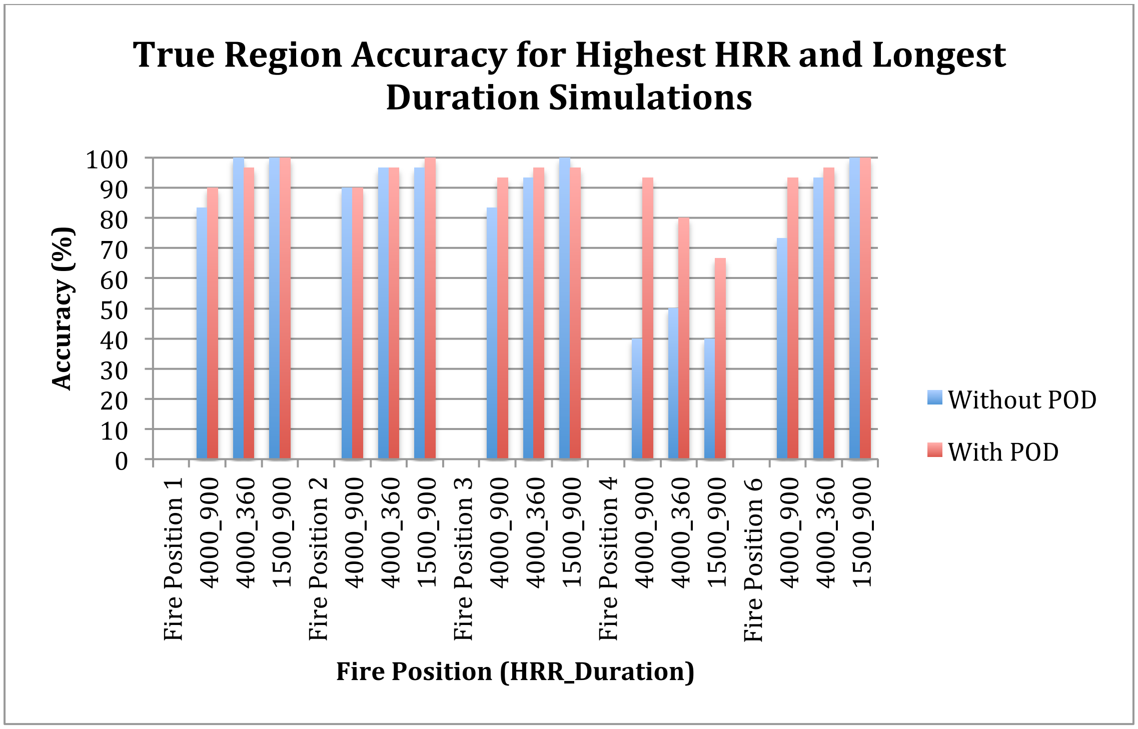


Figure G-46: True Region Accuracy for Highest HRR and Longest Duration Simulations

A limitation with these results comes from the imposed definition of accuracy. A participant was classified as accurate when the region identified as the true region was selected, regardless of the number of regions selected by the participant. In other words, there was a potential for an artificially high accuracy rate should the participant select all of the regions for all scenarios. To evaluate the possibility of an artificially high accuracy rate due to the imposed definition of accuracy, each scenario was evaluated to identify what percentage of participants selected each region with and without the POD (Figures G-47 through G-78).

The data is inconsistent with participants selecting all regions to artificially increase accuracy rates (Figures G-47 through G-78). The general trend identified was that a greater number of regions with a higher percentage of participants were identified when scenarios had higher heat release rates and longer durations. The majority of the scenarios, however, had greater percentage of participants selecting the true region of origin, followed by a slight decrease in percentages of participants selecting 1-2 adjacent regions around the true origin, and then a consistent decrease in percentages and number of regions selected moving away from the true origin. Many of the scenarios had several regions not selected at all by any of the participants, which is further evidence that an artificially high accuracy rate was not influenced by random selection of all regions.

Another general trend identified was that participants would select greater regions when using the POD on scenarios with higher heat release rates and longer durations. This was expected as it was explicitly listed in the instructions of the POD to select all regions that had either a plume generated pattern or undetermined generated pattern identified.   Fire position 4 had the greatest variability in regions selected and percentages identified.

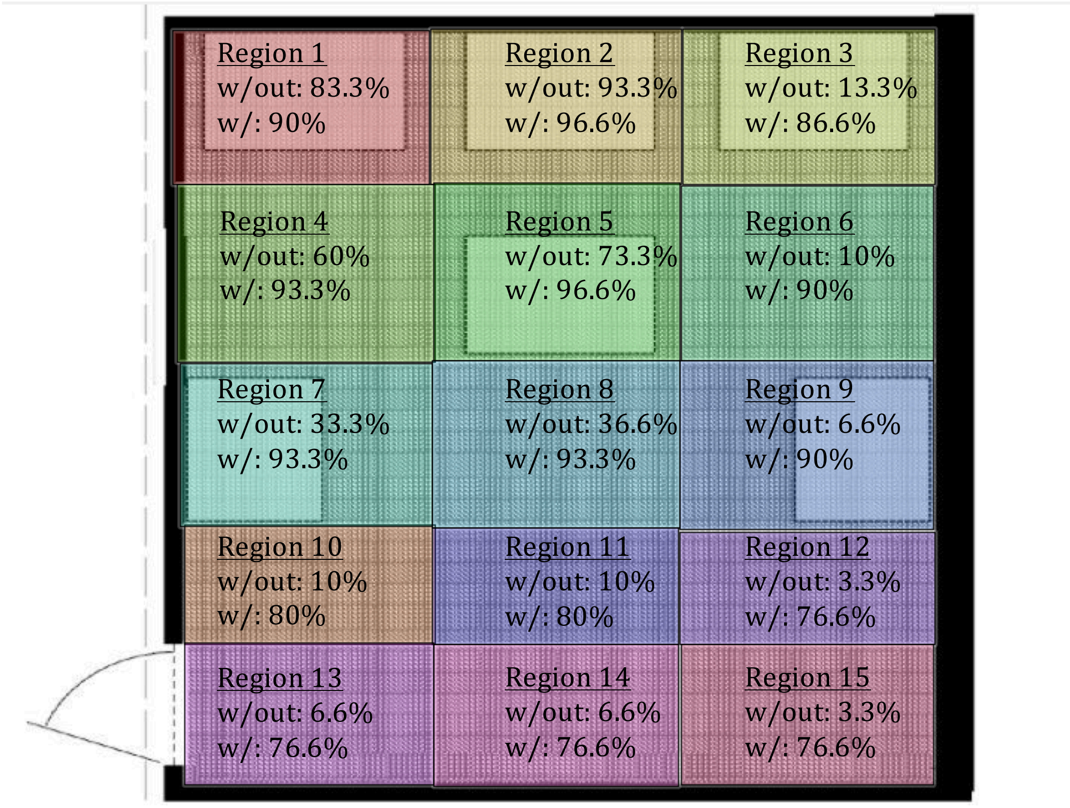


Figure G-47: Regions selected for fire position #1, 4000kW, 900s

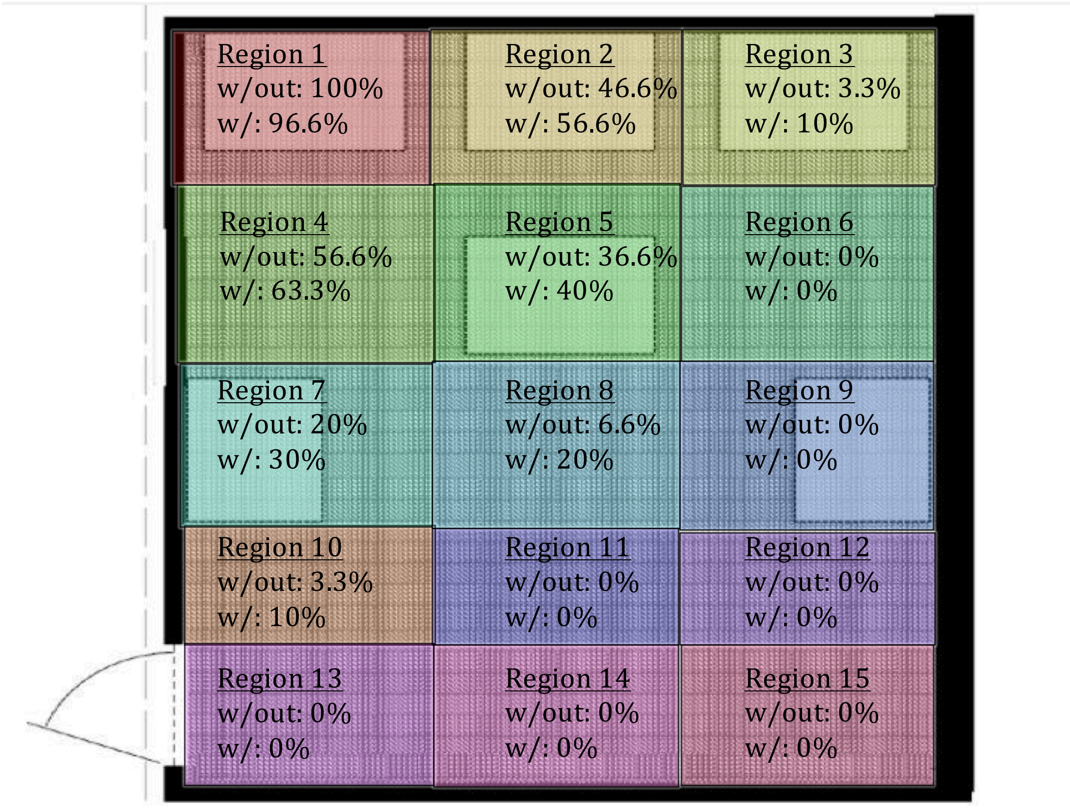


Figure G-48: Regions selected for fire position #1, 4000kW, 360s

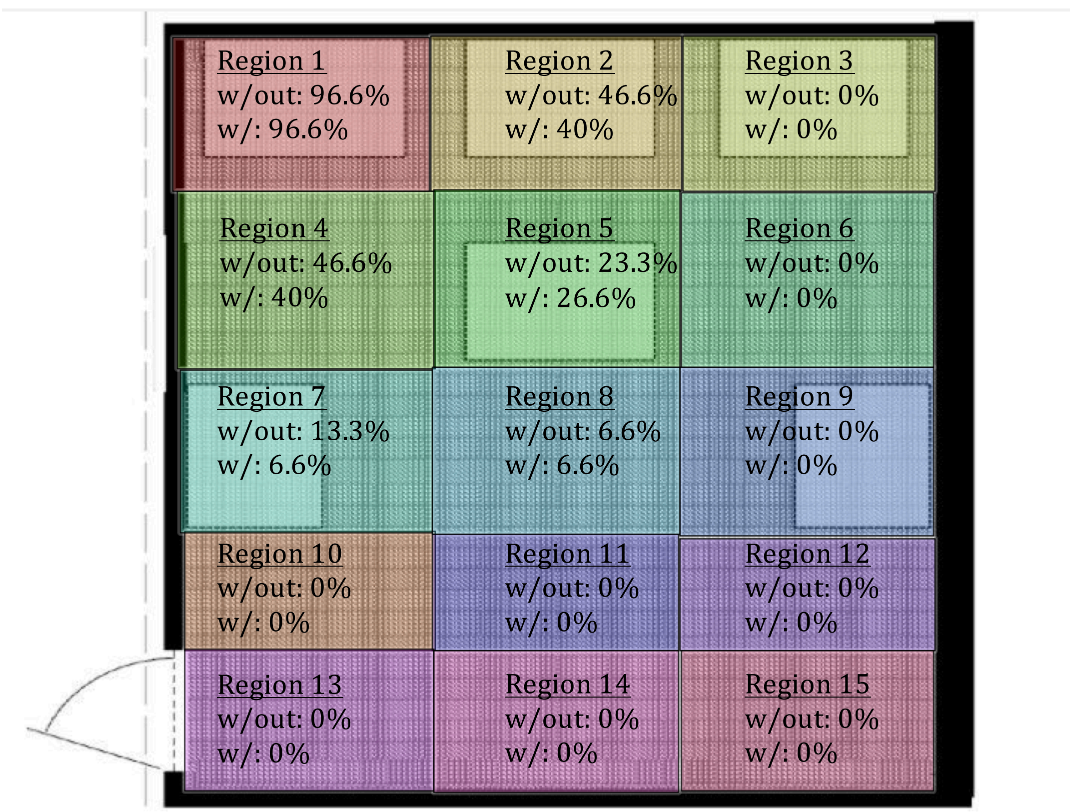


Figure G-49: Regions selected for fire position #1, 4000kW, 120s

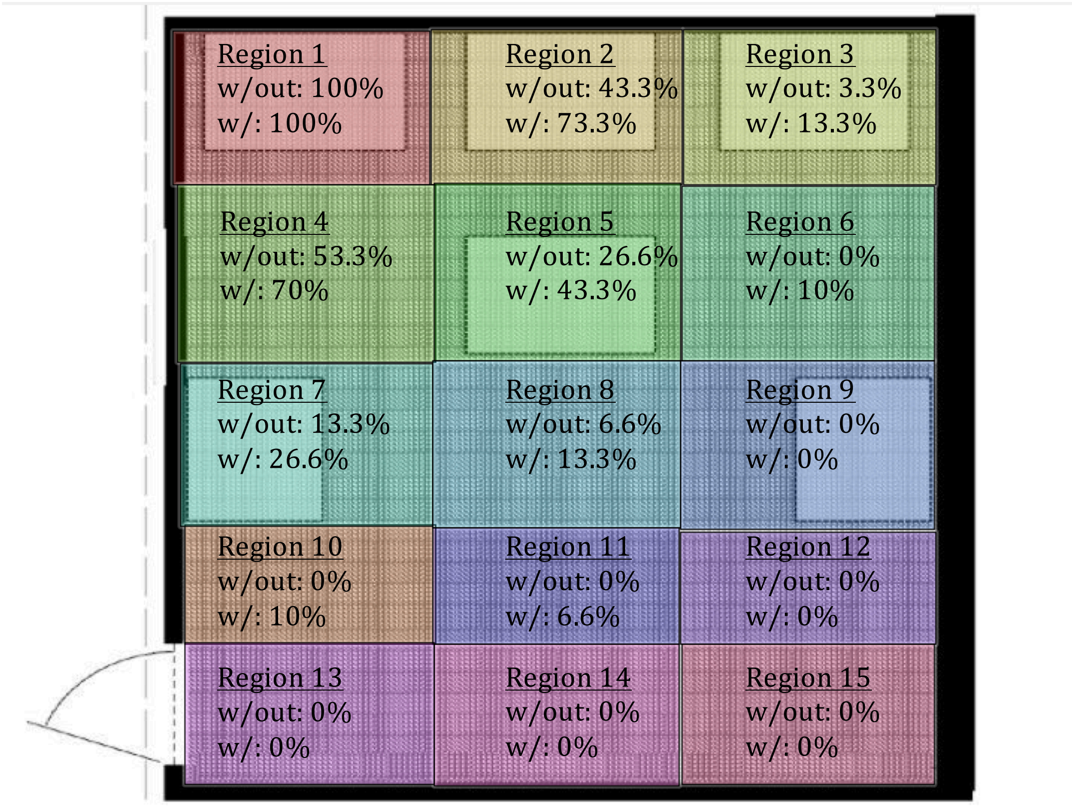


Figure G-50: Regions selected for fire position #1, 1500kW, 900s

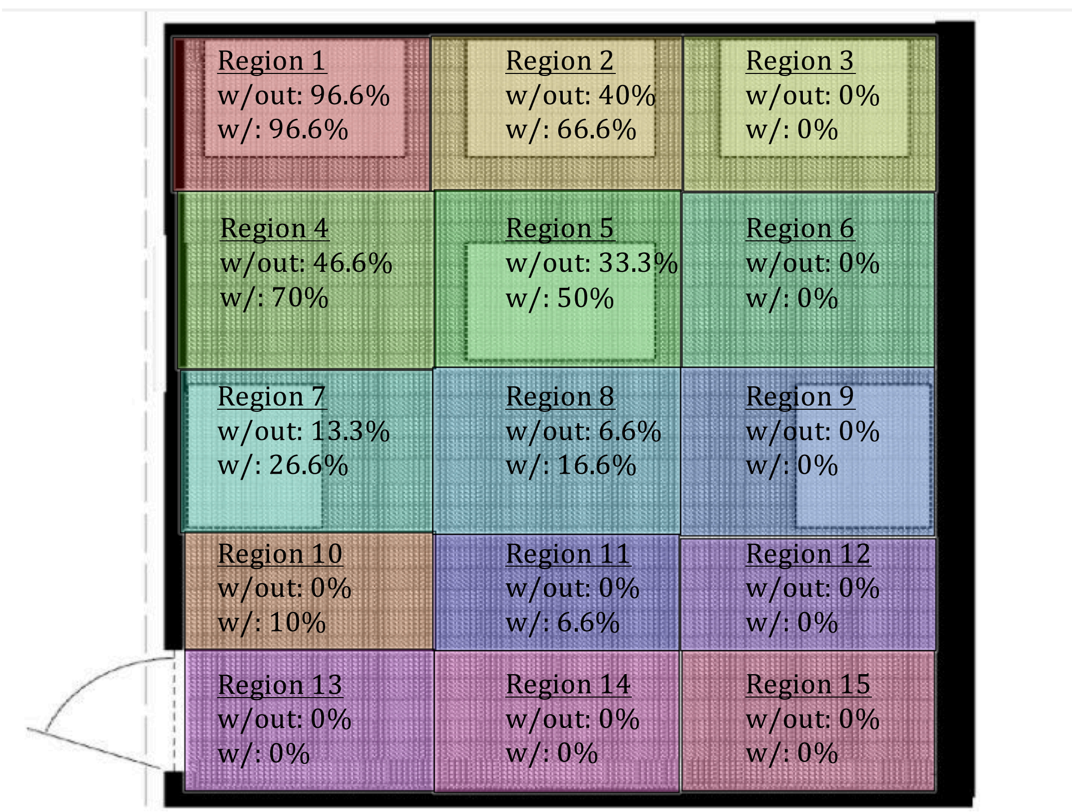


Figure G-51: Regions selected for fire position #1, 1500kW, 360s

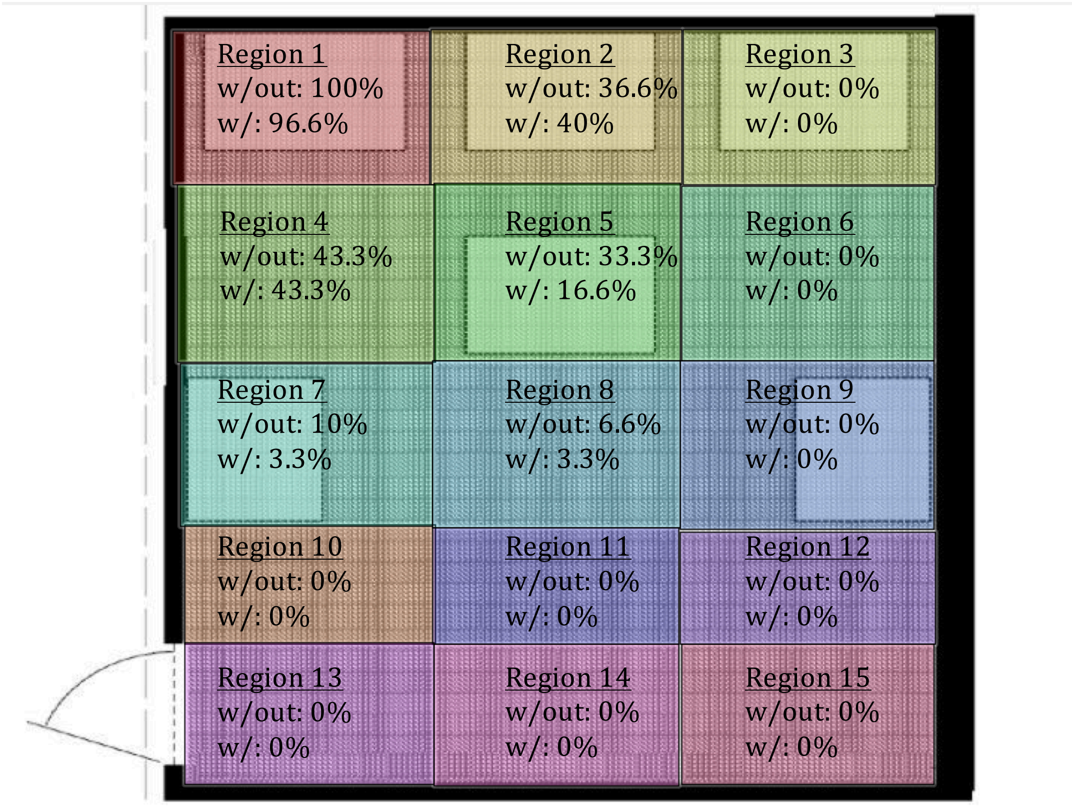


Figure G-52: Regions selected for fire position #1, 1500kW, 120s

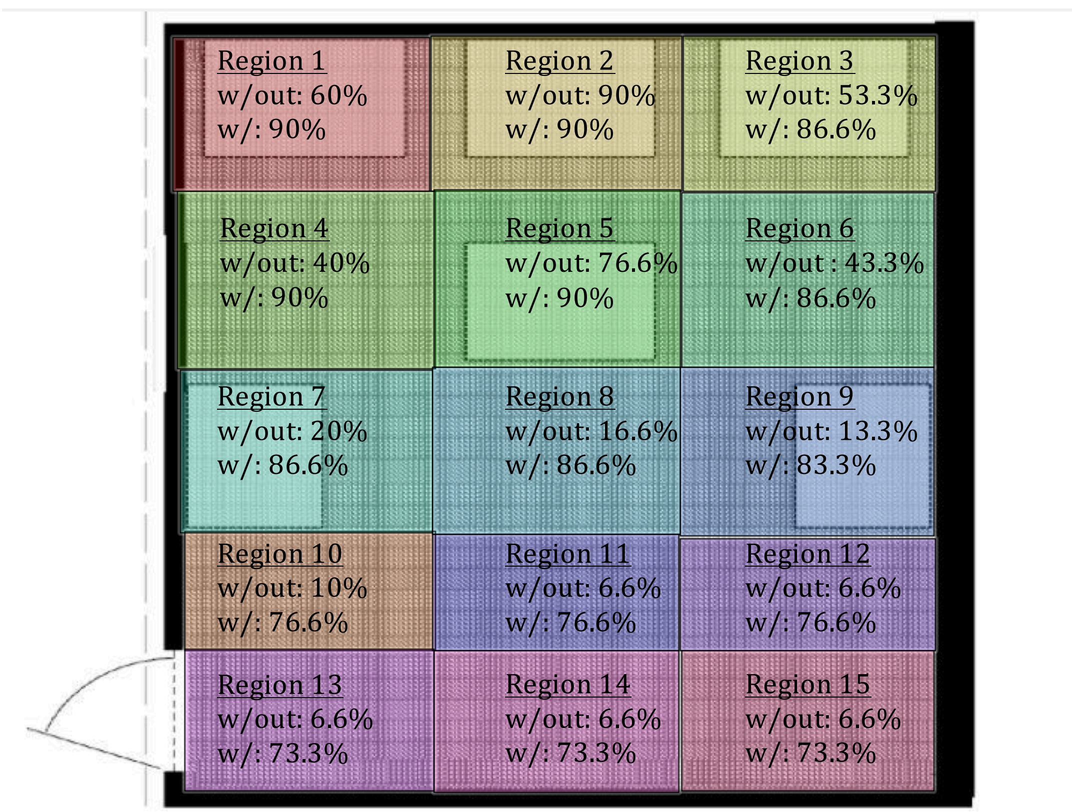


Figure G-53: Regions selected for fire position #2, 4000kW, 900s

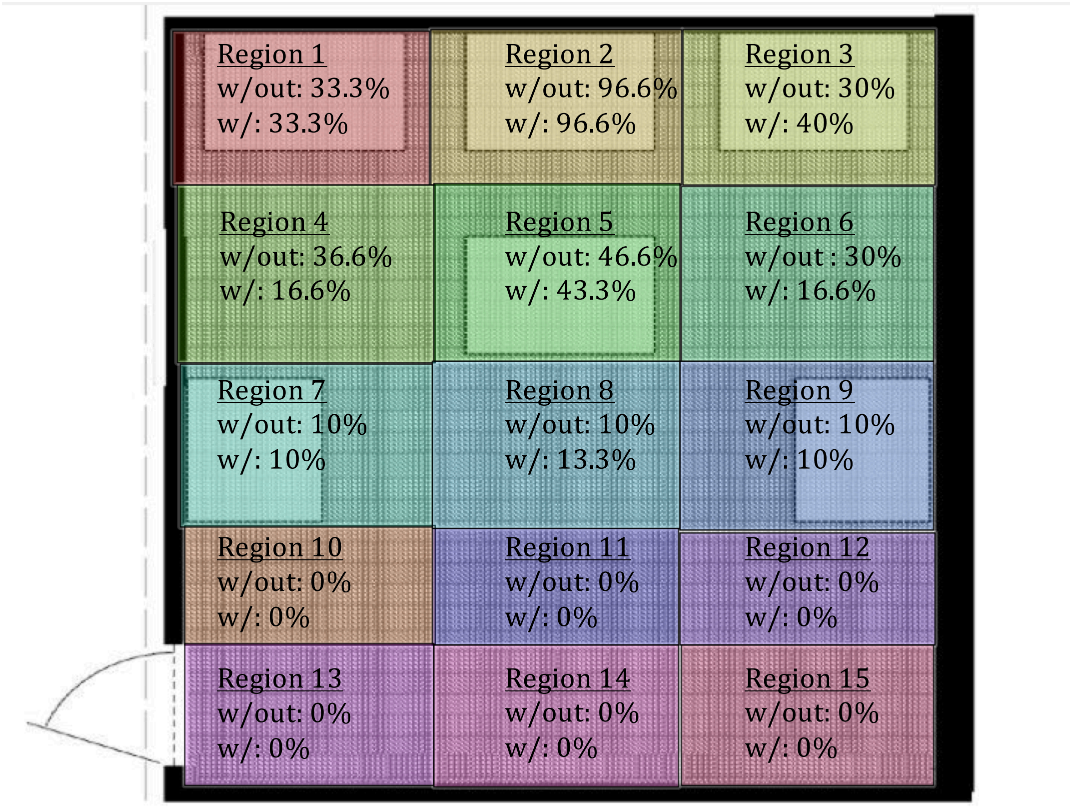


Figure G-54: Regions selected for fire position #2, 4000kW, 360s

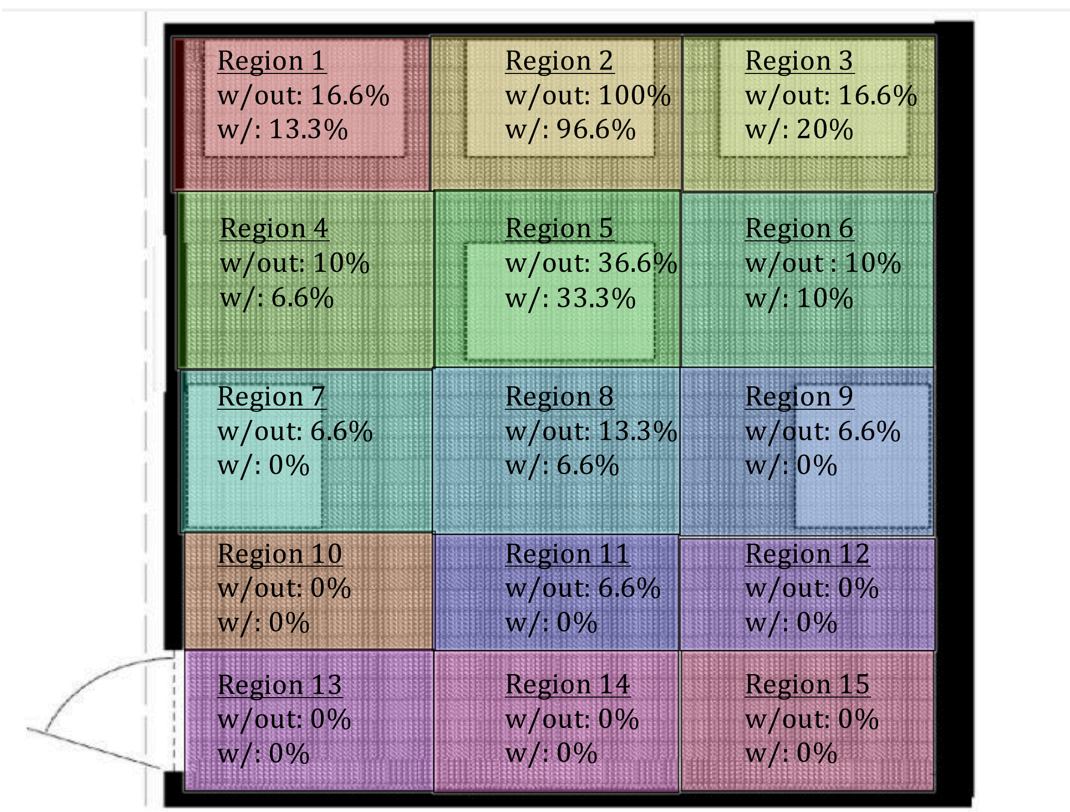


Figure G-55: Regions selected for fire position #2, 4000kW, 120s

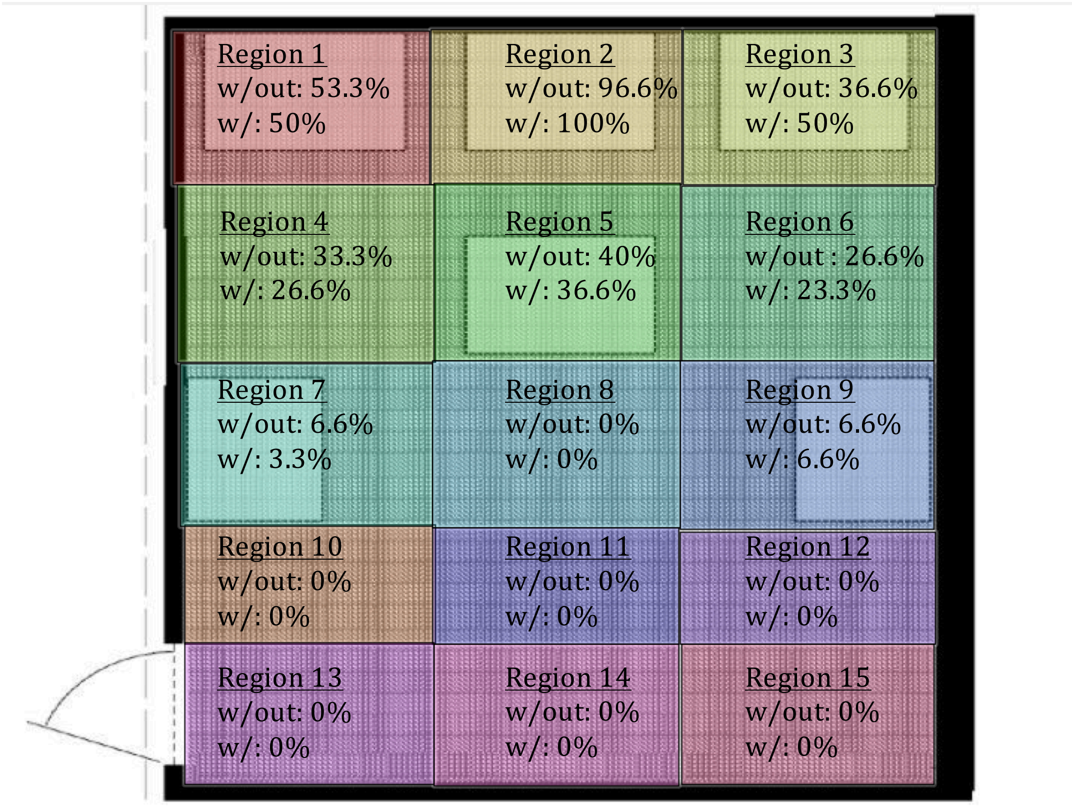


Figure G-56: Regions selected for fire position #2, 1500kW, 900s

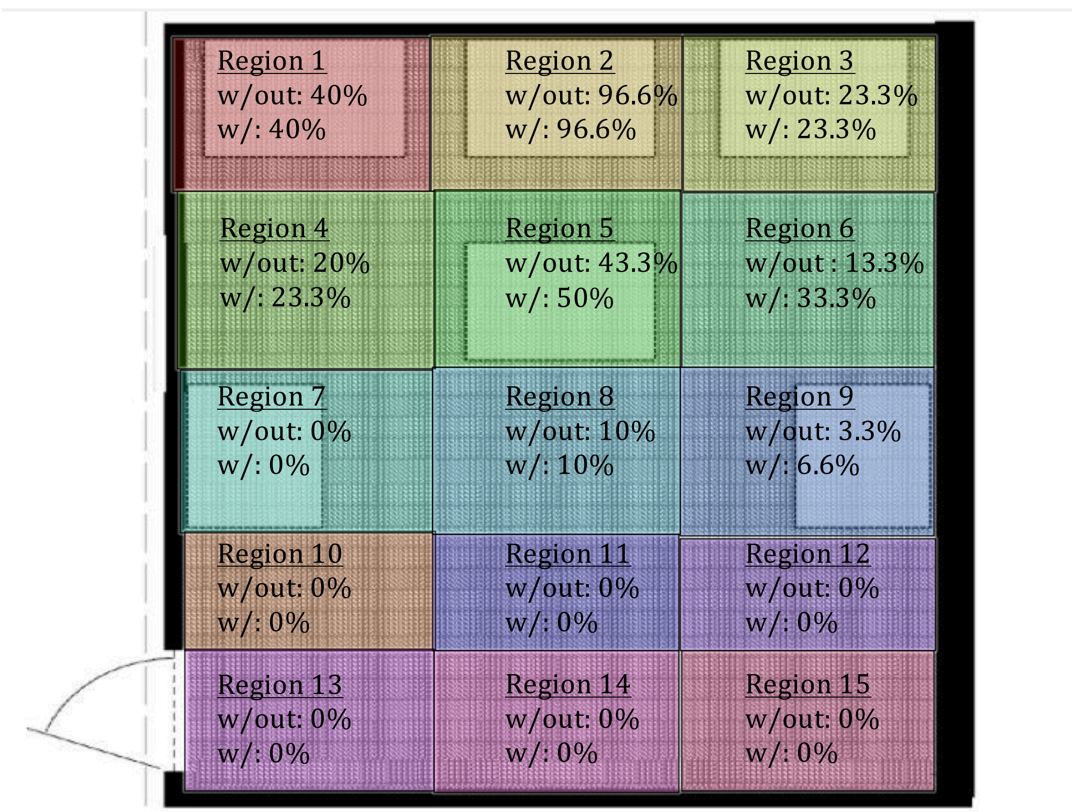


Figure G-57: Regions selected for fire position #2, 1500kW, 360s

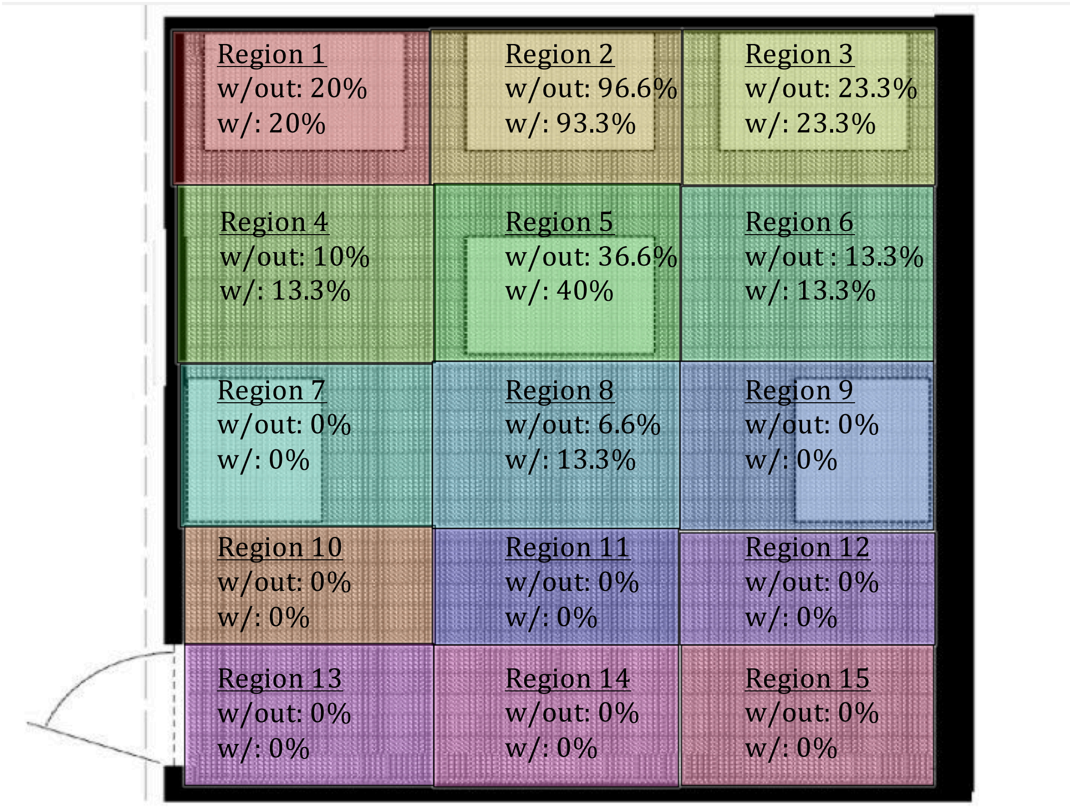


Figure G-58: Regions selected for fire position #2, 1500kW, 120s

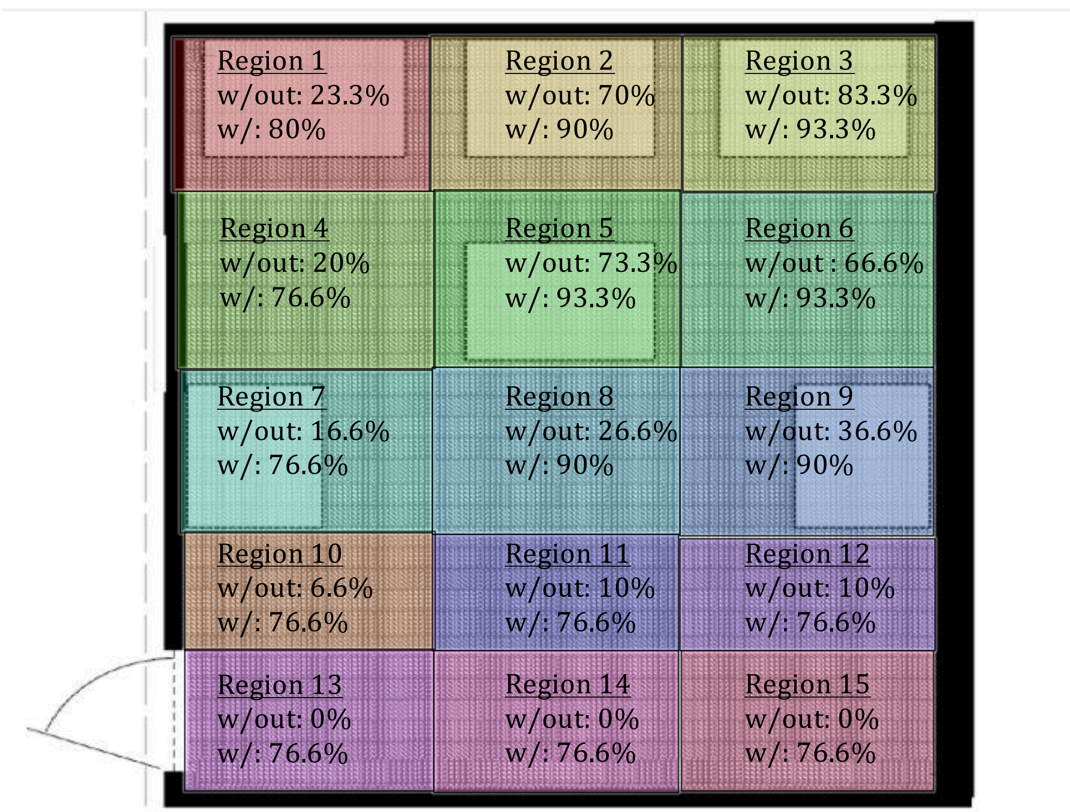


Figure G-59: Regions selected for fire position #3, 4000kW, 900s

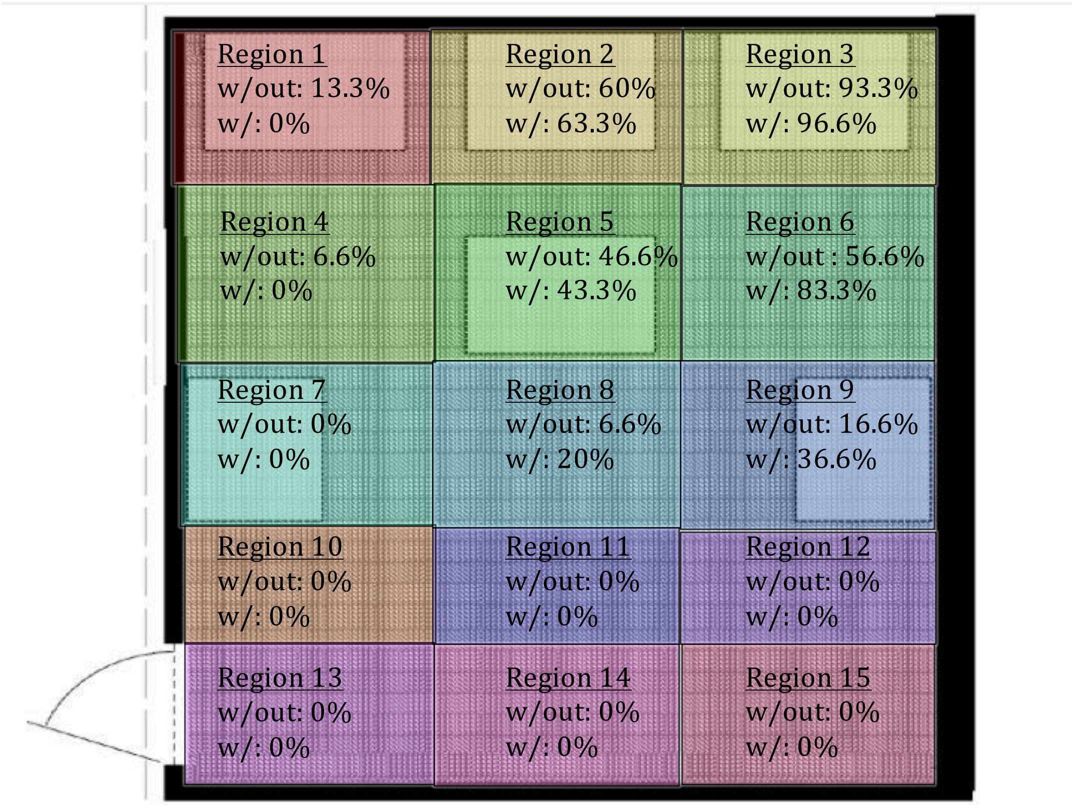


Figure G-60: Regions selected for fire position #3, 4000kW, 360s

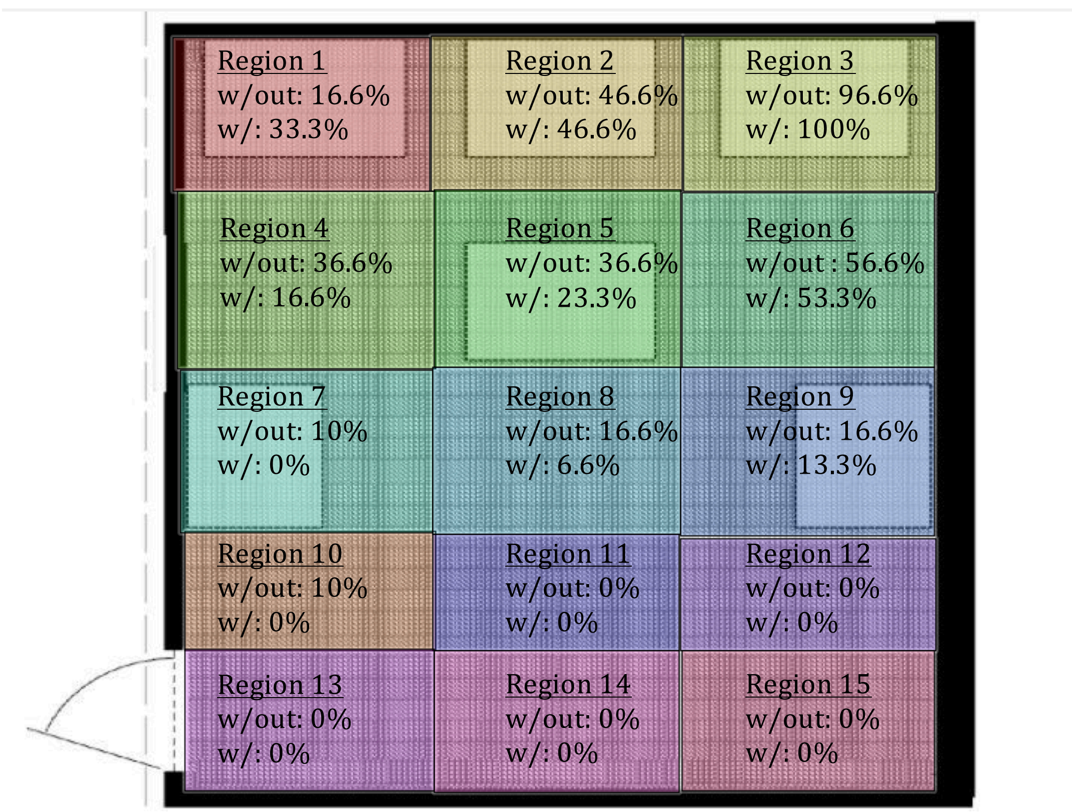


Figure G-61: Regions selected for fire position #3, 4000kW, 120s

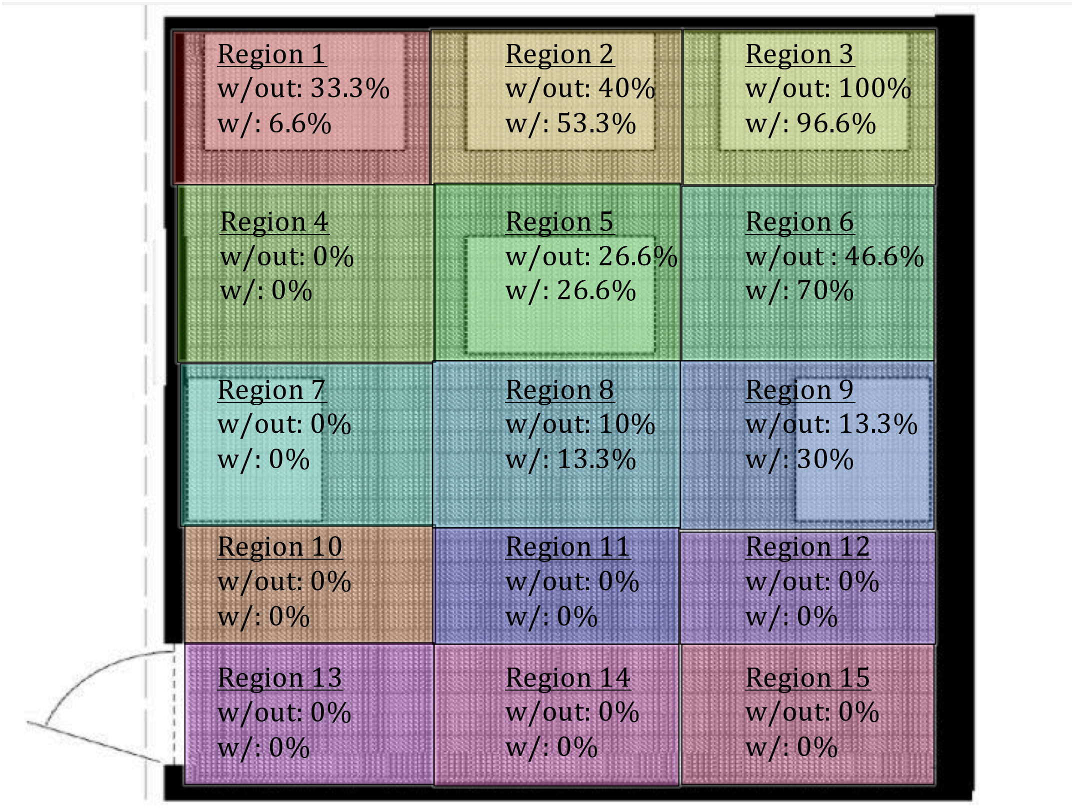


Figure G-62: Regions selected for fire position #3, 1500kW, 900s

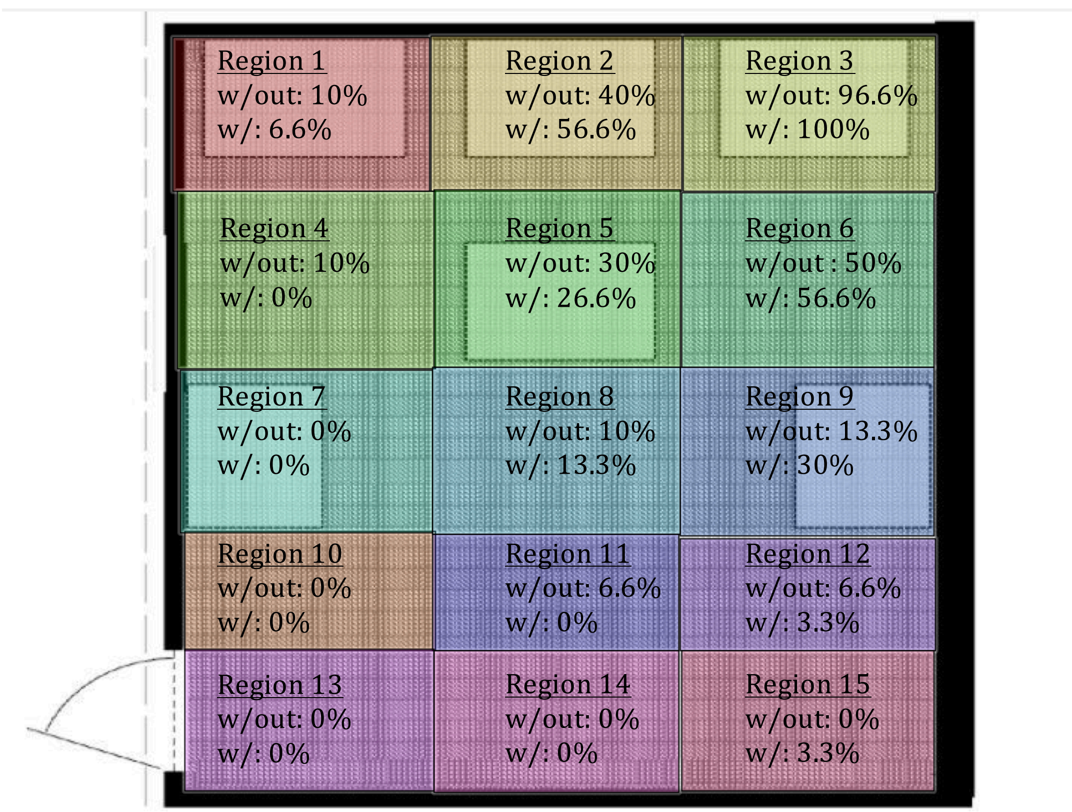


Figure G-63: Regions selected for fire position #3, 1500kW, 360s

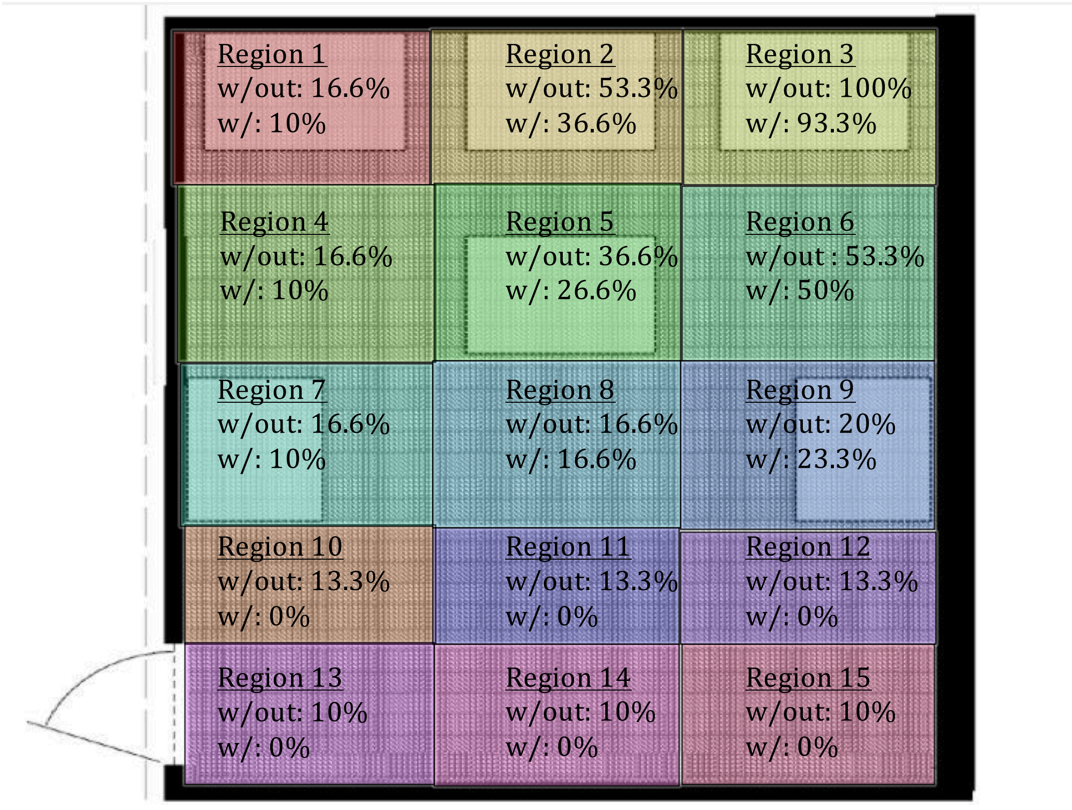


Figure G-64: Regions selected for fire position #3, 1500kW, 120s

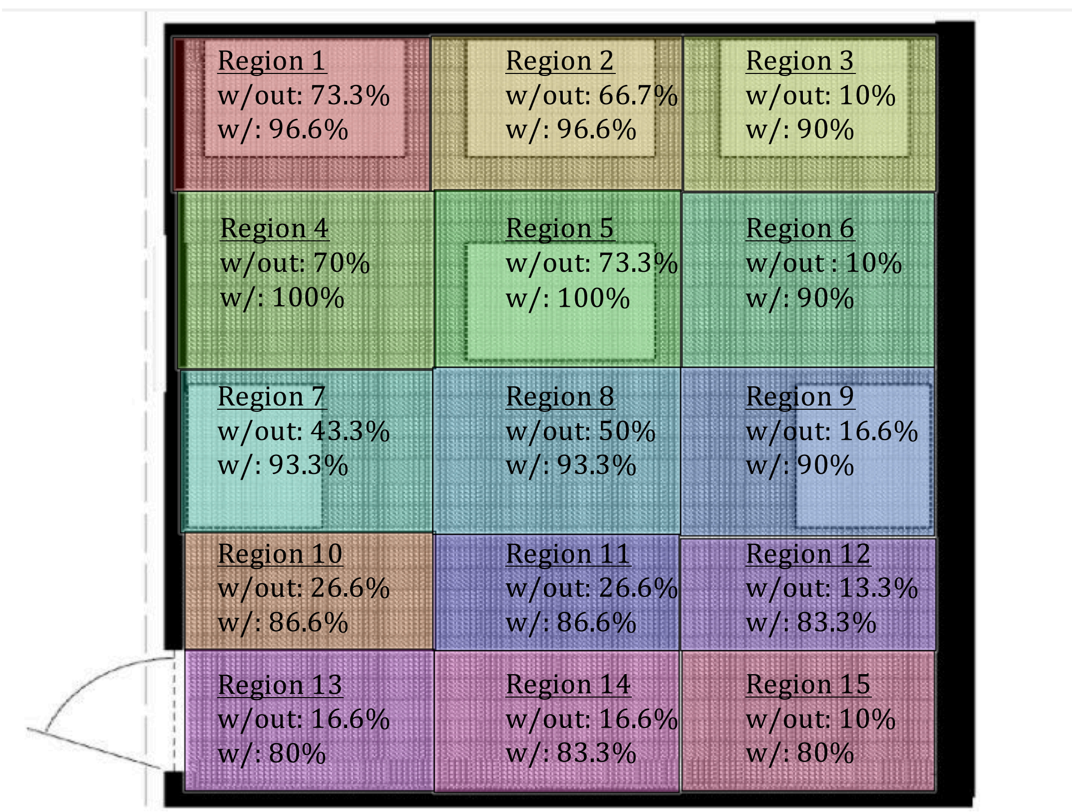


Figure G-65: Regions selected for fire position #4, 4000kW, 900s

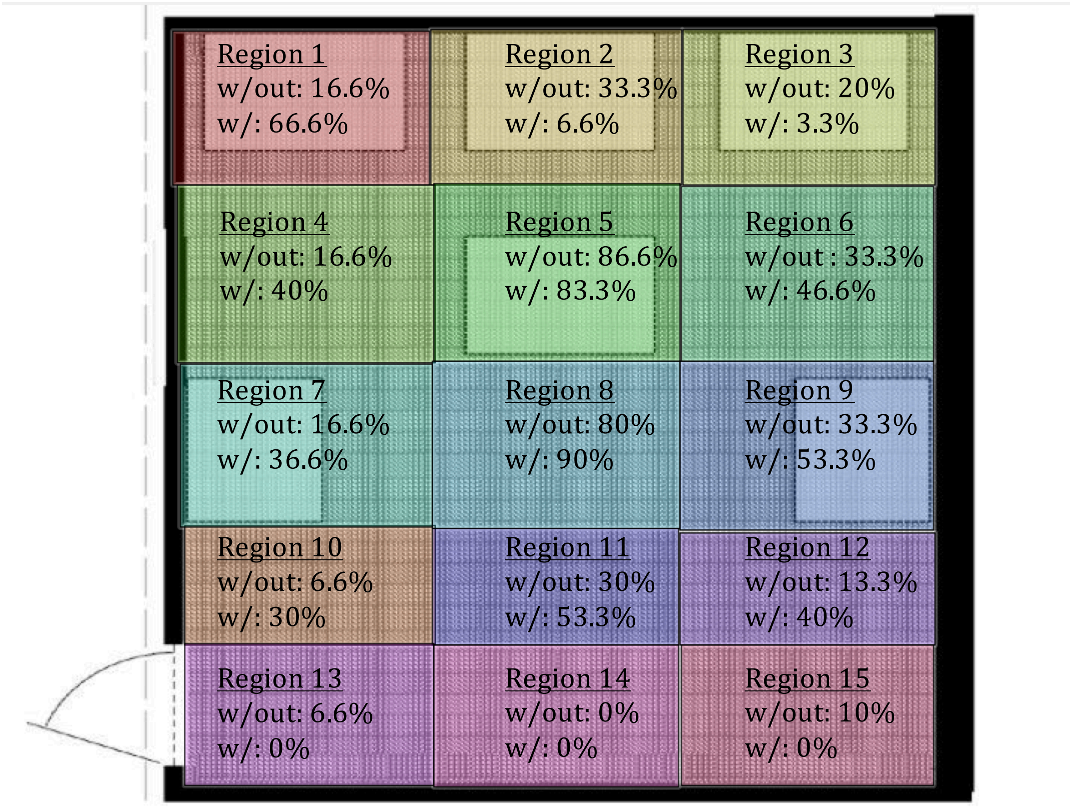


Figure G-66: Regions selected for fire position #4, 4000kW, 360s

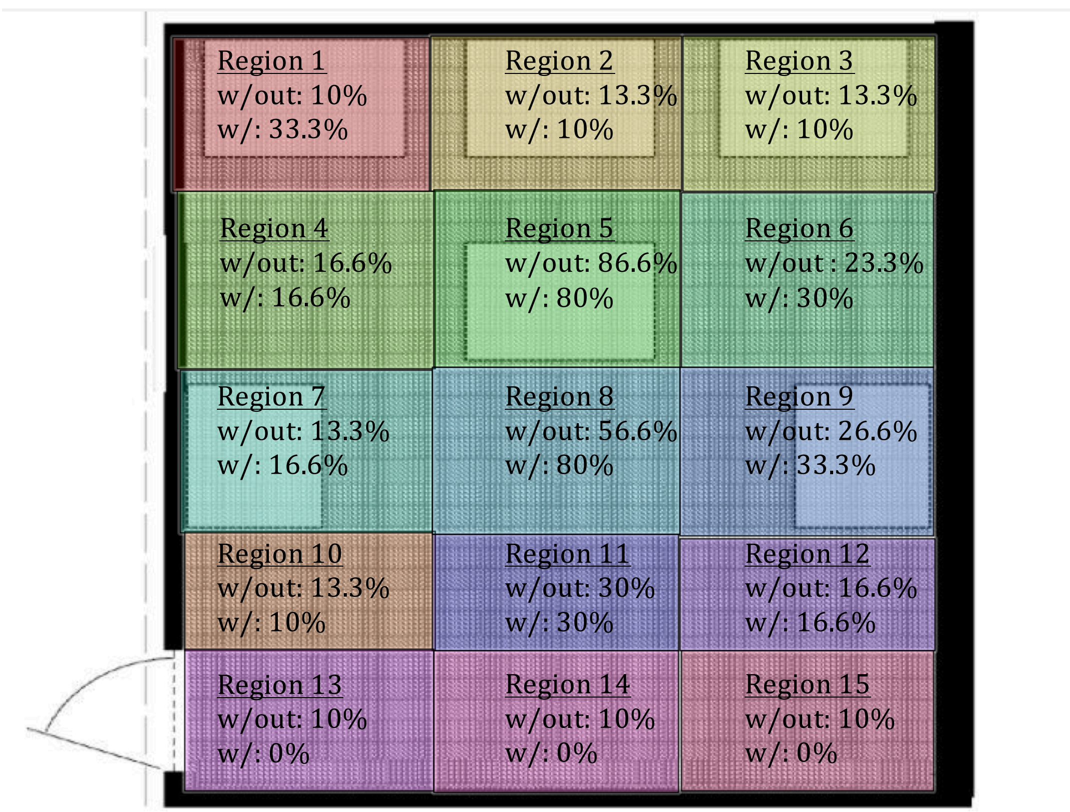


Figure G-67: Regions selected for fire position #4, 4000kW, 120s

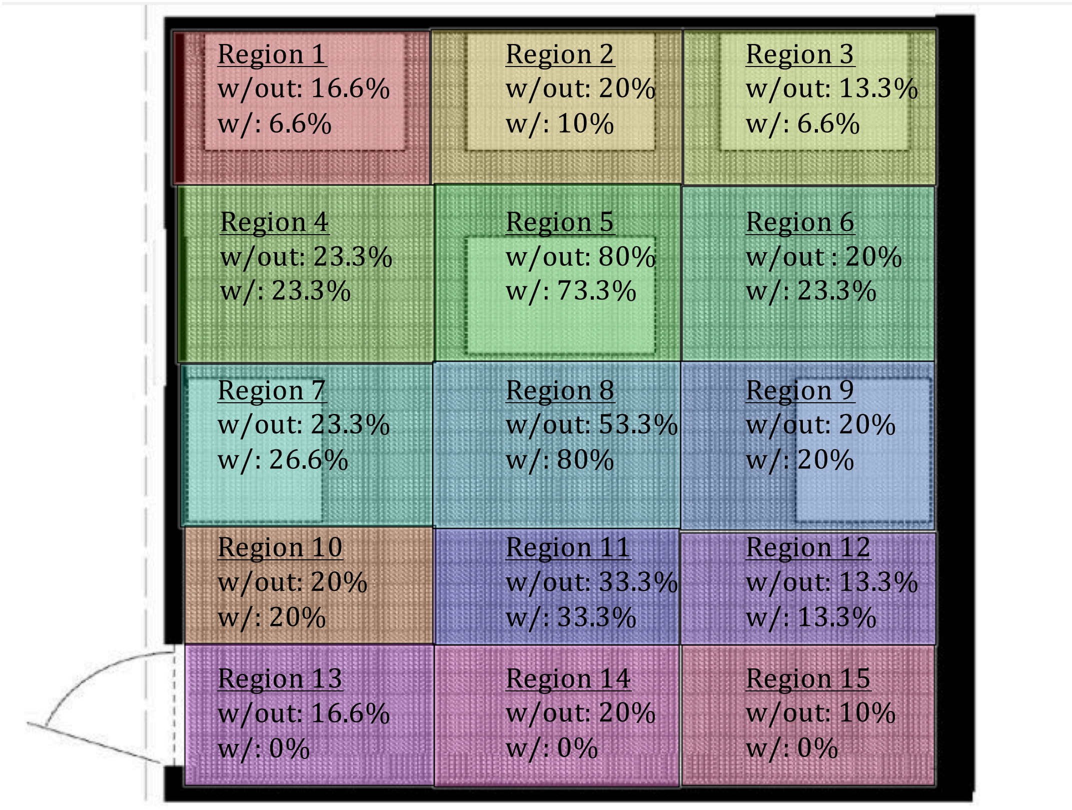


Figure G-68: Regions selected for fire position #4, 1500kW, 900s

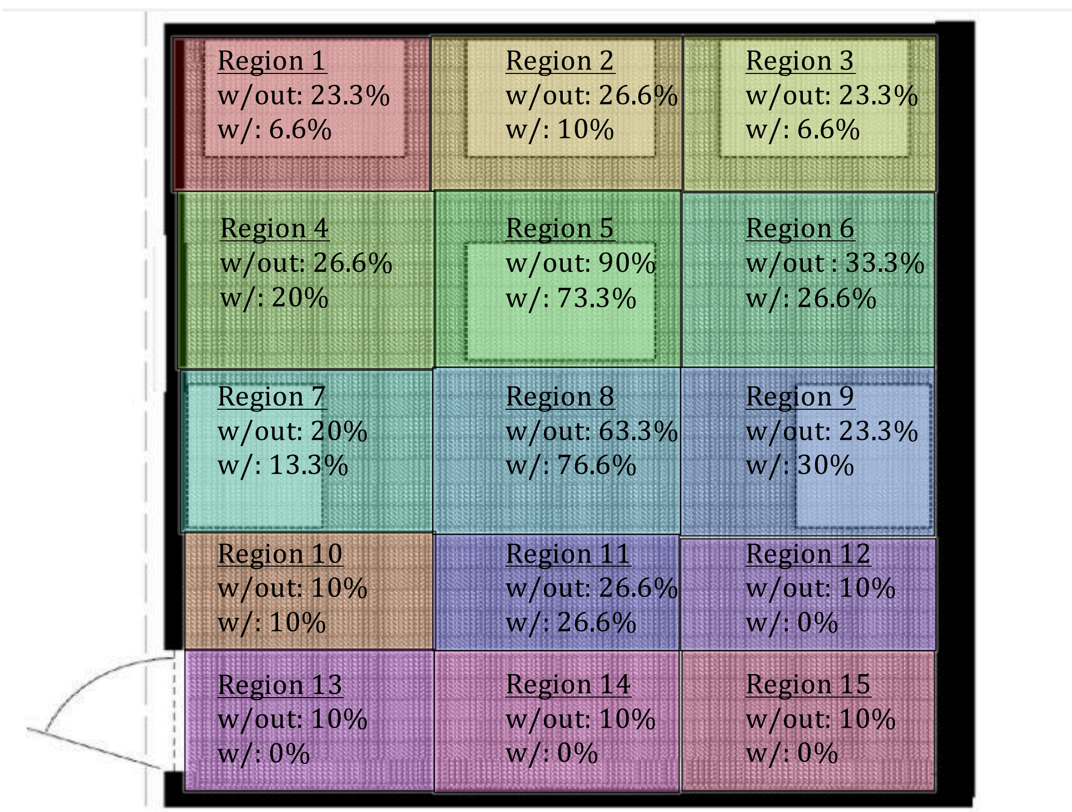


Figure G-69: Regions selected for fire position #4, 1500kW, 360s

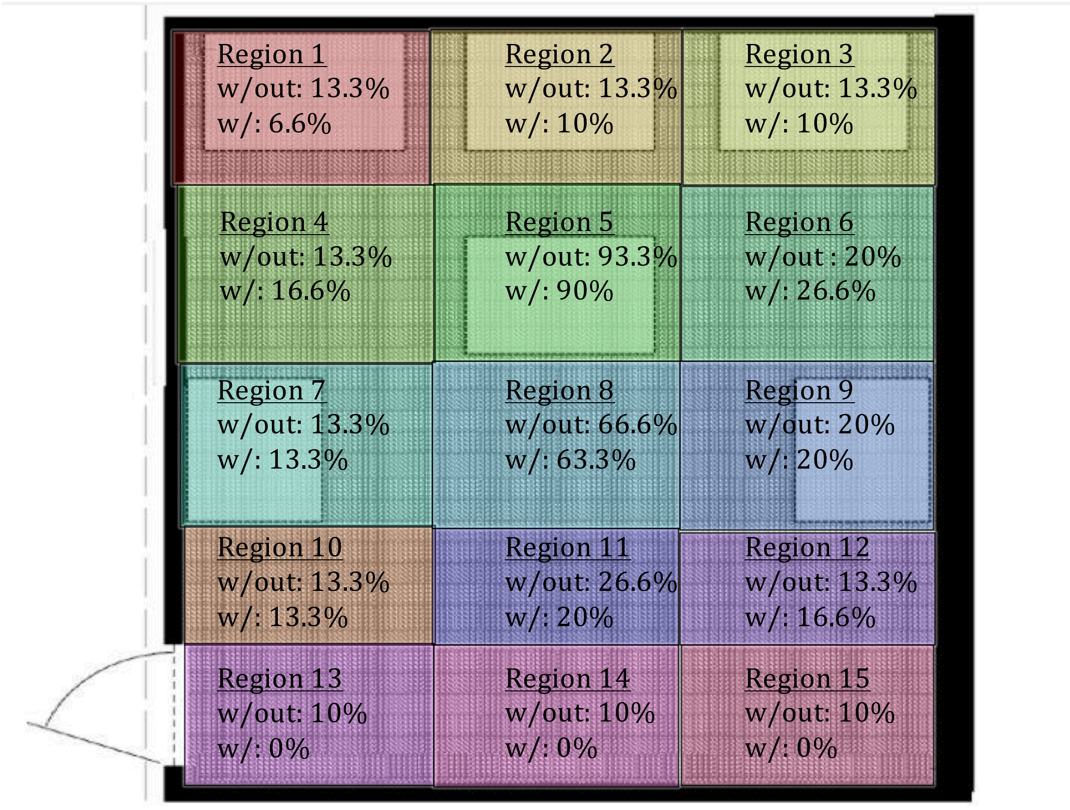


Figure G-70: Regions selected for fire position #4, 1500kW, 120s

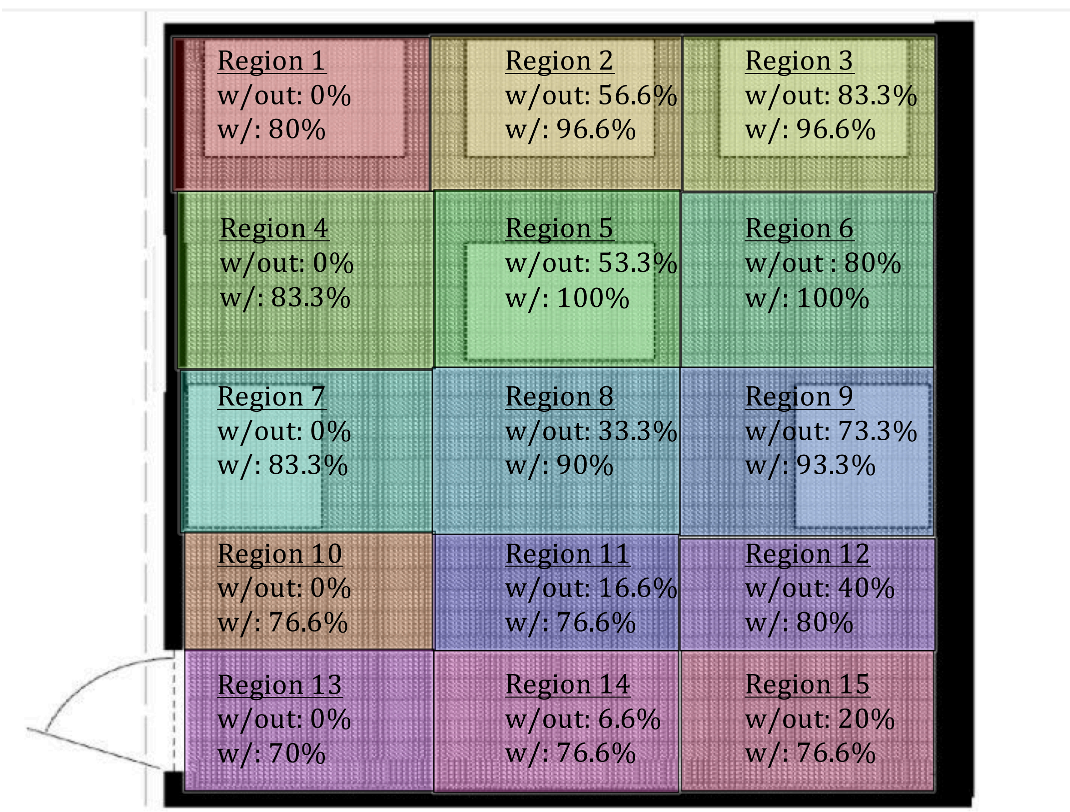


Figure G-71: Regions selected for fire position #6, 4000kW, 900s

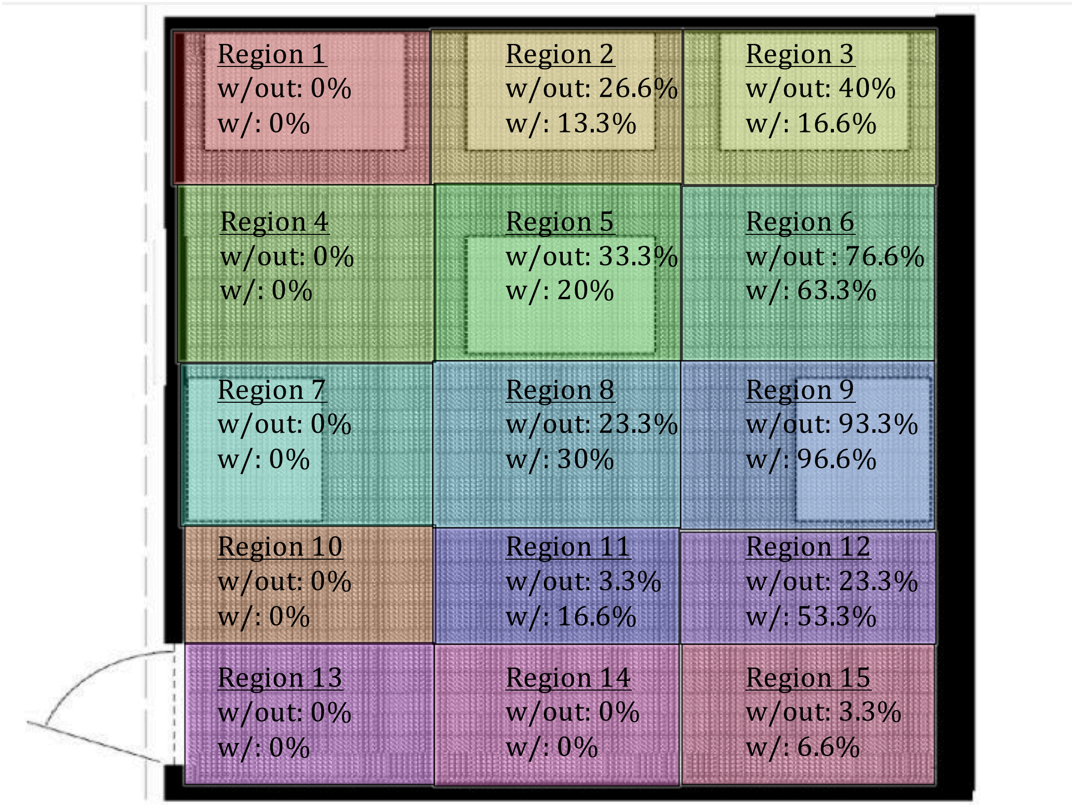


Figure G-72: Regions selected for fire position #6, 4000kW, 360s

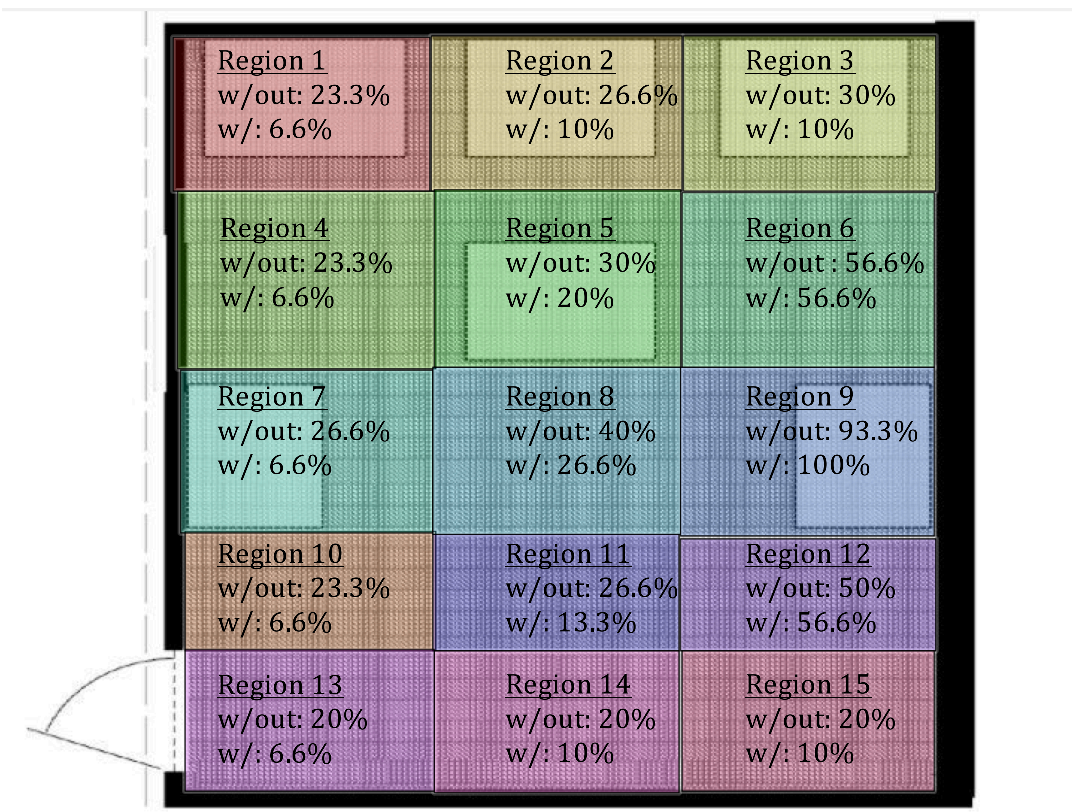


Figure G-73: Regions selected for fire position #6, 4000kW, 120s

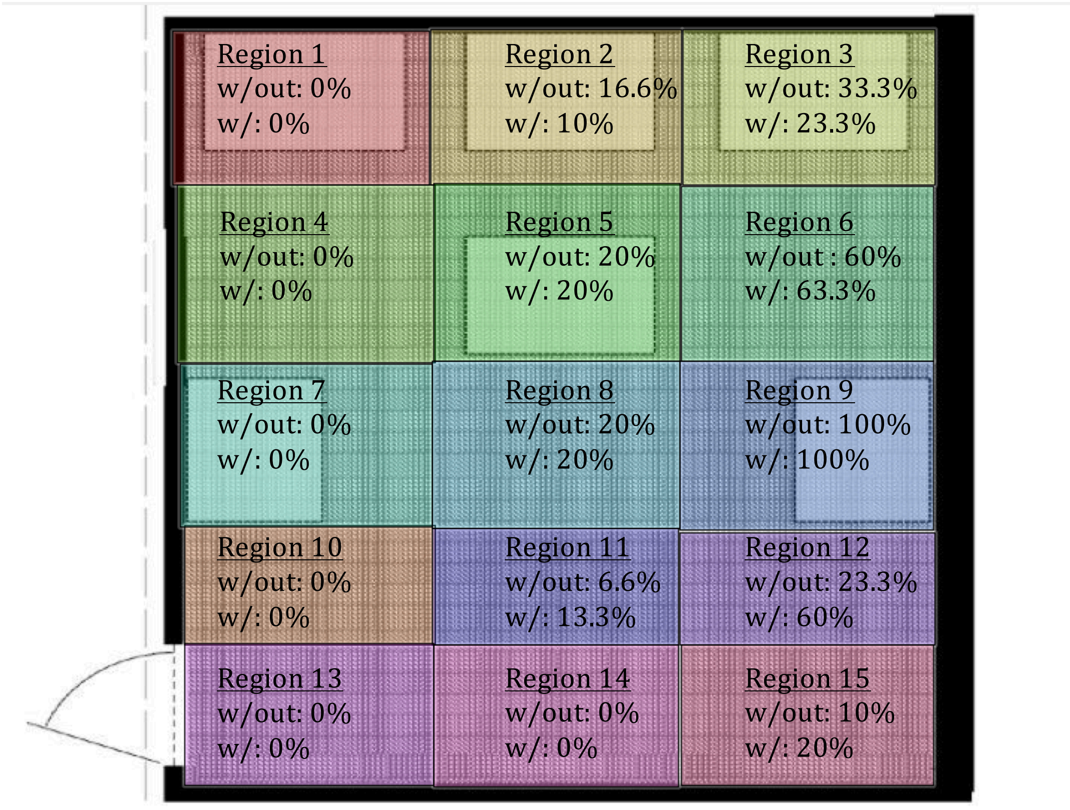


Figure G-74: Regions selected for fire position #6, 1500kW, 900s

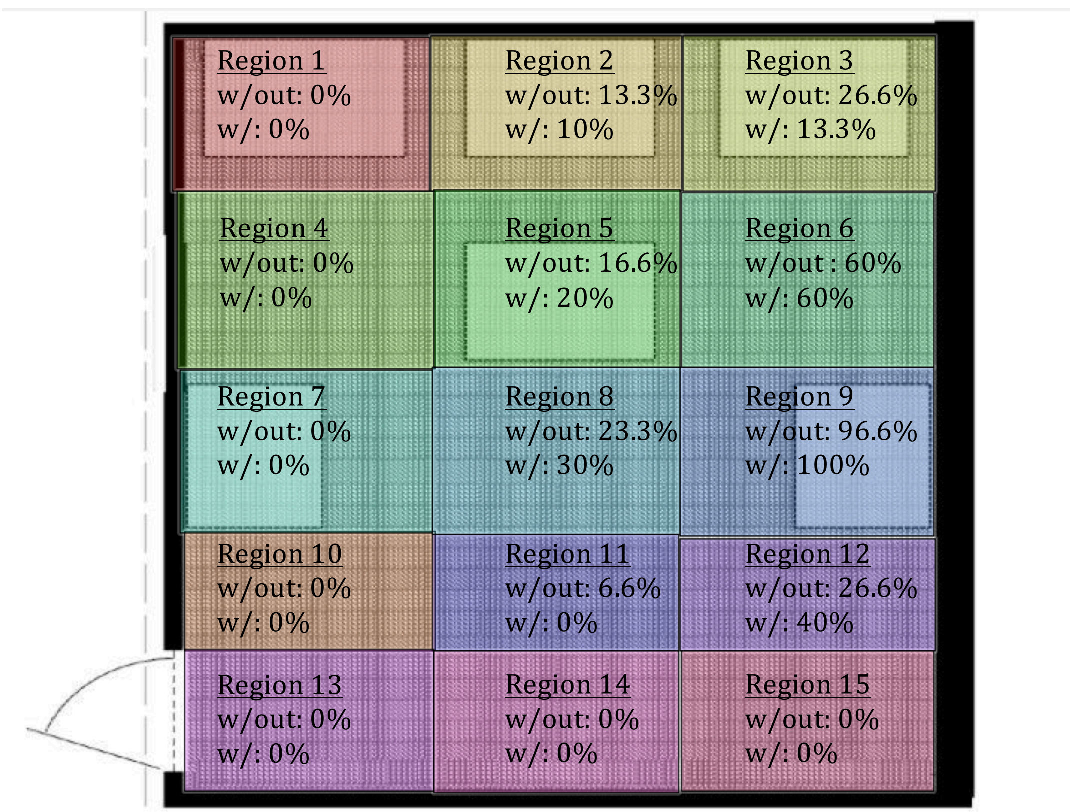


Figure G-75: Regions selected for fire position #6, 1500kW, 360s

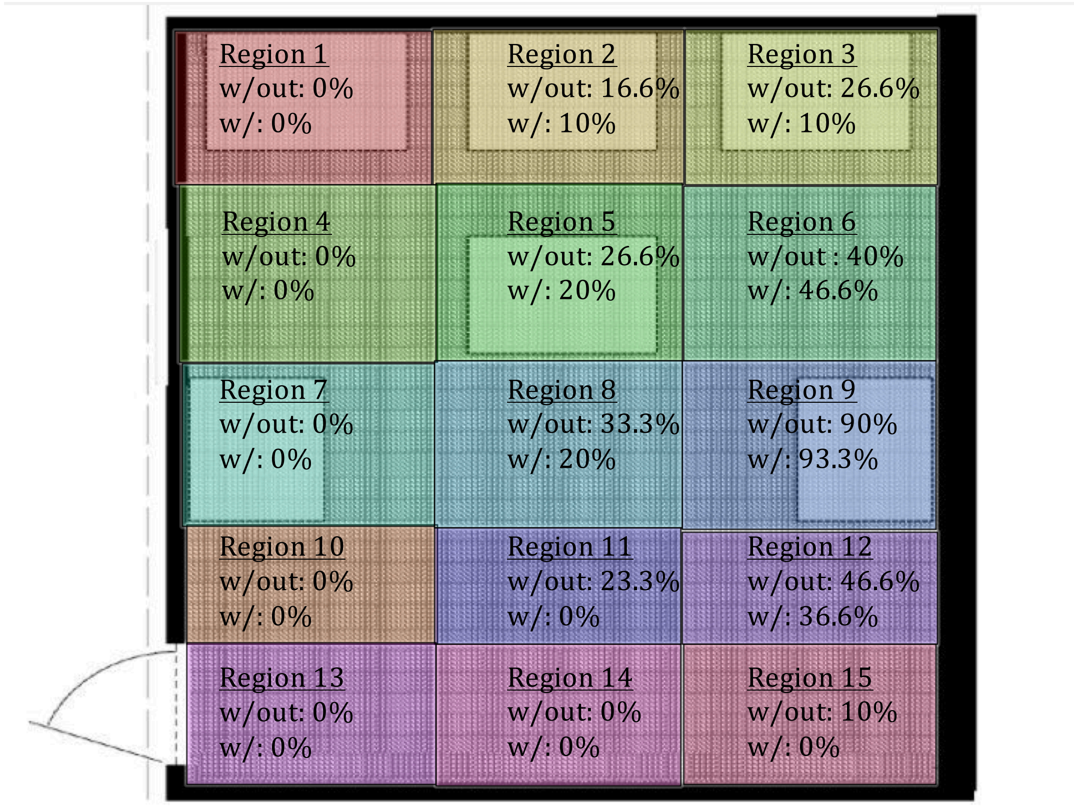


Figure G-76: Regions selected for fire position #6, 1500kW, 120s

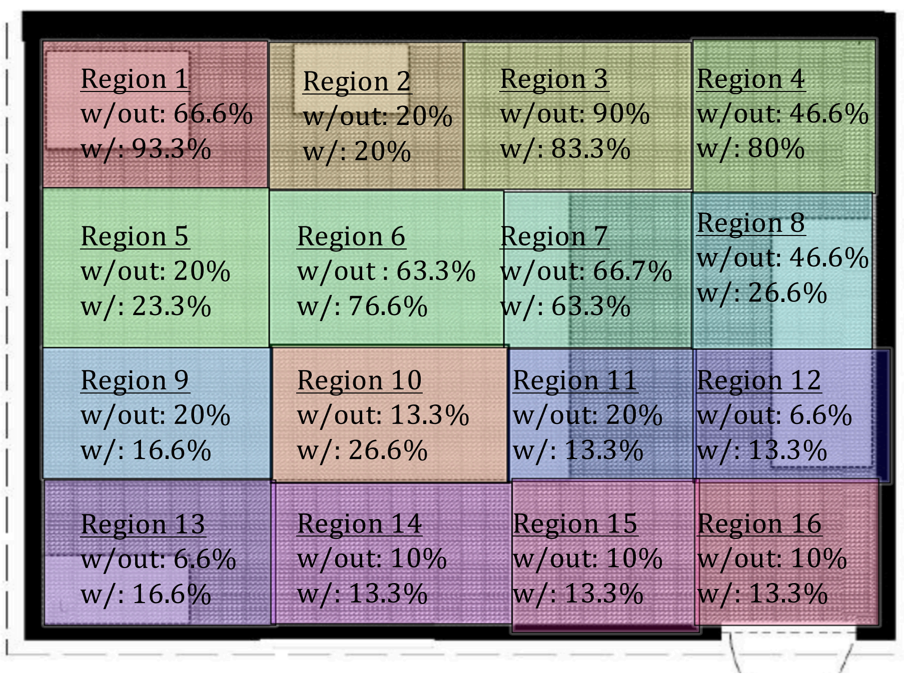


Figure G-77: Regions selected for ATF

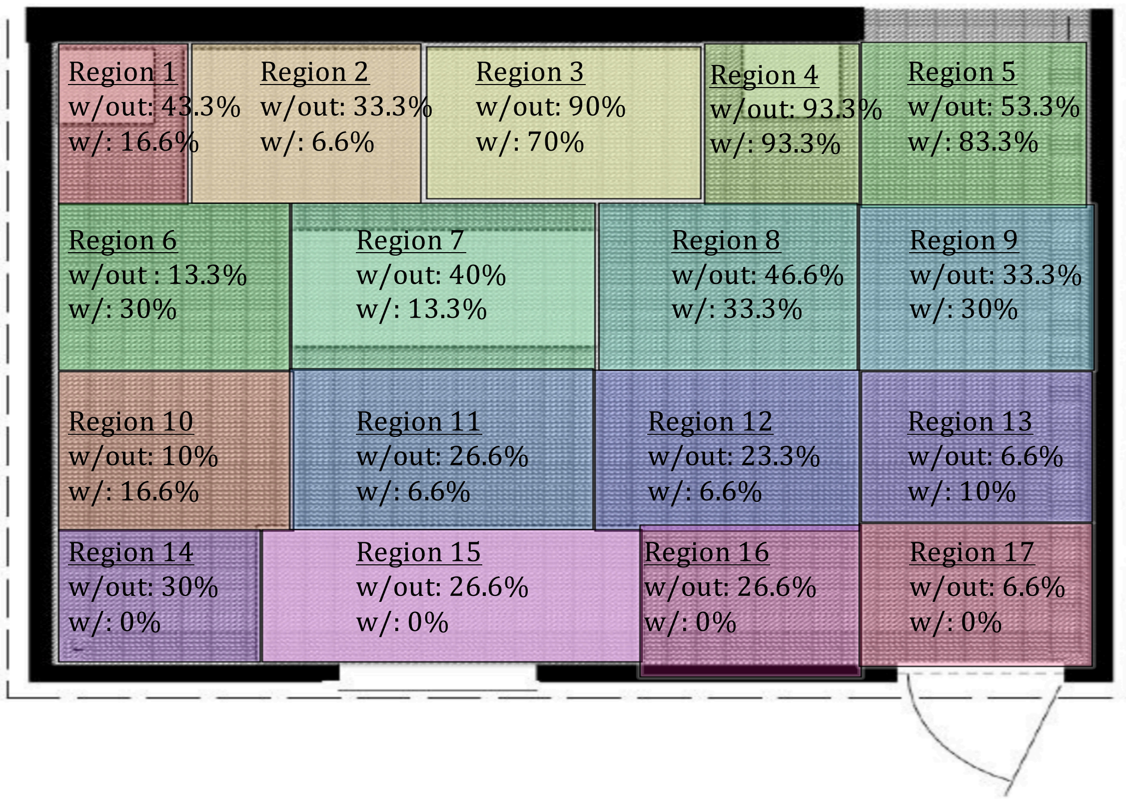


Figure G-78: Regions selected for FIODS

G.2.2 Method Accuracy Charts

The next validation test evaluated which region(s) the participants selected as their area of origin in comparison to what regions should have been selected as identified by accurate use of the POD. The participant was classified as accurate if they selected the exact region(s) that reflected the region(s) identified as the area of origin from the POD. A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 16 out of 32 scenarios (50%), a decrease in accuracy when using the POD in 10 out of 32 (31%), and no change in accuracy when using the POD in 6 out of 32 scenarios (19%) (Table G-6). None of the ten scenarios that decreased in accuracy when using the POD were shown to be statistically significant. It was found that 3 out of the 16 scenarios (19%) that were shown to increase in accuracy when using the POD were statistically significant (Table G-6). Overall there is a statistically significant increase in accuracy rates for the method regions when the POD was used (z=2.11, p=.04) (Table G-6). The nonparametric Wilcoxon test is a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed.

Table G-6: Validation Results – Comparison of Method Accuracy

Overall Comparison of Method Accuracy Rates without and with the POD			
	Number of scenarios	**Total scenarios**	**%**
Increasing accuracy with the method	16	32	50
No change in accuracy	6	32	19
Decreasing accuracy with method	10	32	31
Statistical Significance Evaluation			
	# showing significant increase	**Total increasing scenarios**	**%**
Statistically significant increase (alpha=.05)	3	16	19
Test for Overall Significance			
	Without POD	**With POD**	
Mean (μ) accuracy rate	0.83	0.89	
Standard Deviation (σ)	0.12	0.14	
Median accuracy rates	0.78	0.94	
Independent samples t-test to compare means	t=1.71	p=.1	
Wilcoxon two-sample test to compare medians	z=2.11	p=0.04	

To better evaluate any trends with the data, the POD or method region accuracy rates were plotted for each fire position. The general trend with this analysis was that the accuracy decreased for those simulations that had higher heat release rates and longer durations (Figures G-79 through G-83). Fire position 4 had the lowest accuracy rates, however, it had the most significant increases in accuracy when the POD was used. Both of the physical experiments increased in accuracy with the use of the POD. The FIODS study had a statistically significant increase ($p<0.05$) in accuracy when using the POD (Figure G-84).

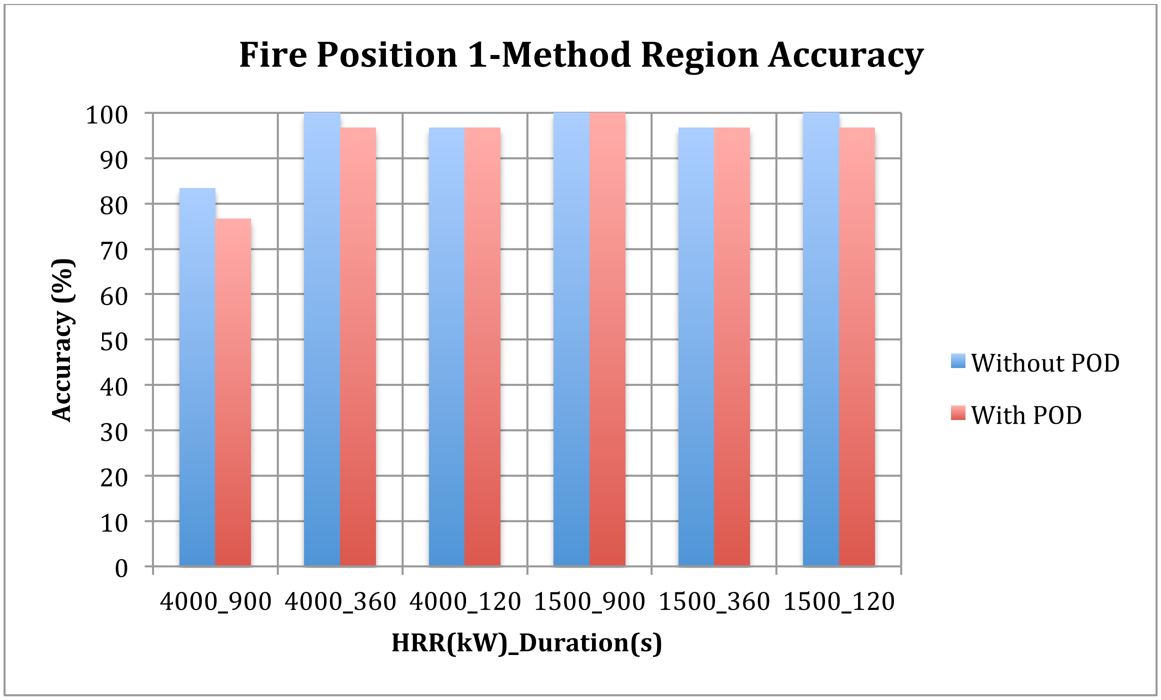


Figure G-79: Fire Position 1 Region Selection Accuracy in Accordance with the POD

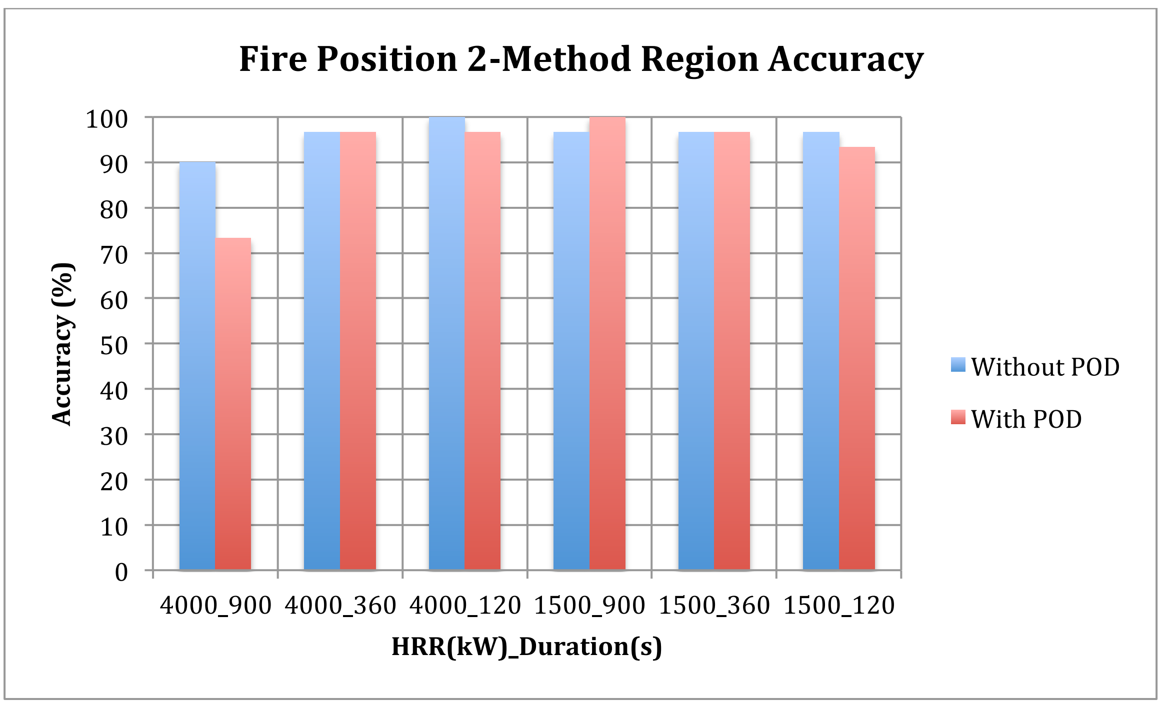


Figure G-80: Fire Position 2 Region Selection Accuracy in Accordance with the POD

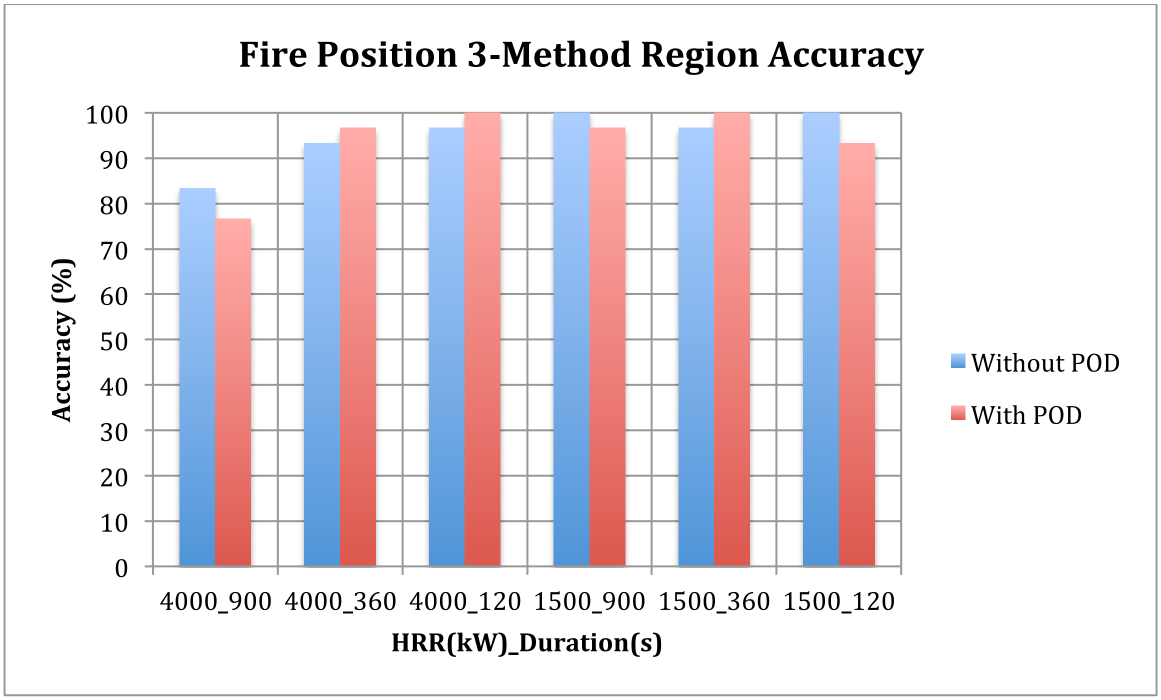


Figure G-81: Fire Position 3 Region Selection Accuracy in Accordance with the POD

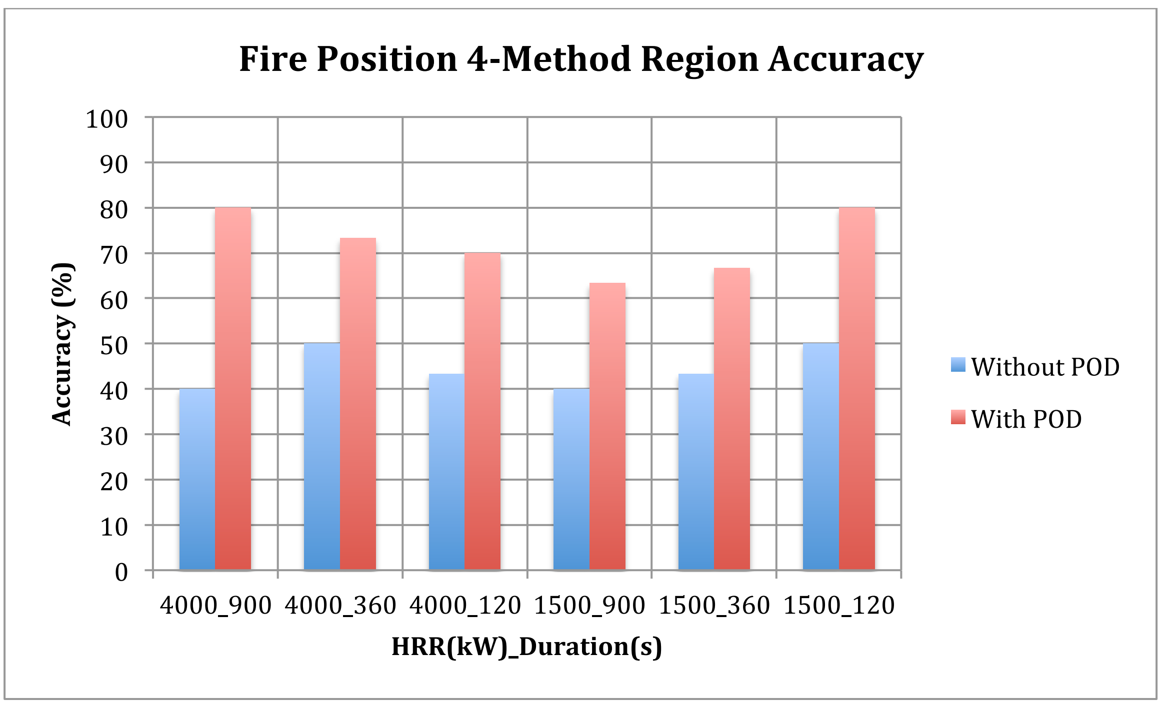


Figure G-82: Fire Position 4 Region Selection Accuracy in Accordance with the POD

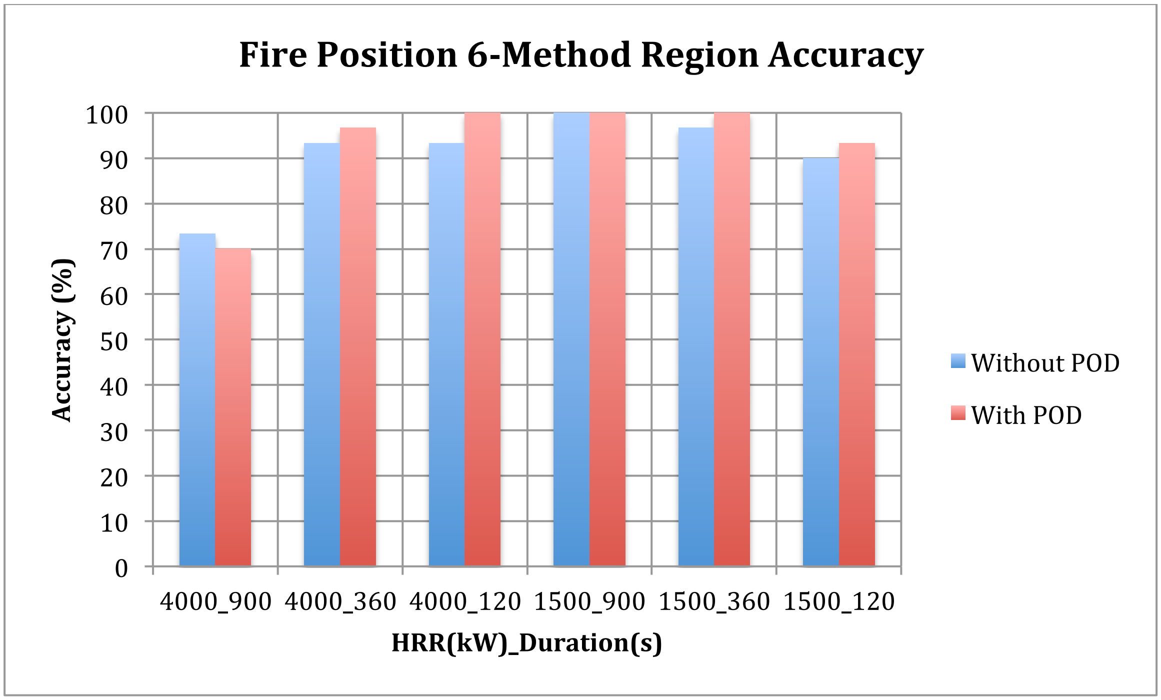


Figure G-83: Fire Position 6 Region Selection Accuracy in Accordance with the POD

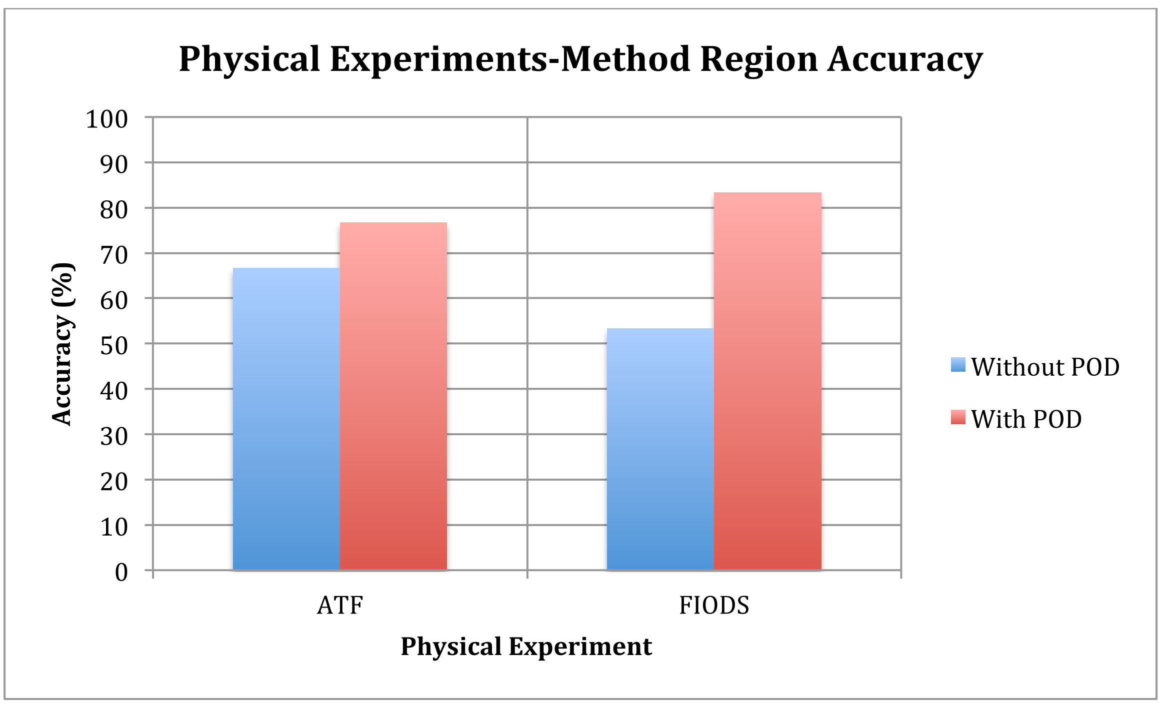


Figure G-84: Physical Experiments Region Selection Accuracy in Accordance with the POD

As the general trend indicated that the greatest variability was identified with the highest heat release rate and longest duration simulations, it was necessary to evaluate the results of these simulations more closely. The highest HRR and longest duration simulations were the 4000kW fires at 360 seconds and 900 seconds, and the 1500kW fire at 900 seconds. Specifically, it was important to evaluate the influence of the POD on these more difficult scenarios. Out of these simulations, 7 performed better with the POD (47%), 1 performed at the same level (6%), and 7 had greater variability (47%) (Table G-7, Figure G-85).

Table G-7: Influence of the POD on the highest HRR and longest duration simulations

	Number of Scenarios	Total scenarios	%
Decreasing Accuracy w/POD	7	15	47
Increasing Accuracy w/POD	7	15	47
No Change in Accuracy	1	15	6

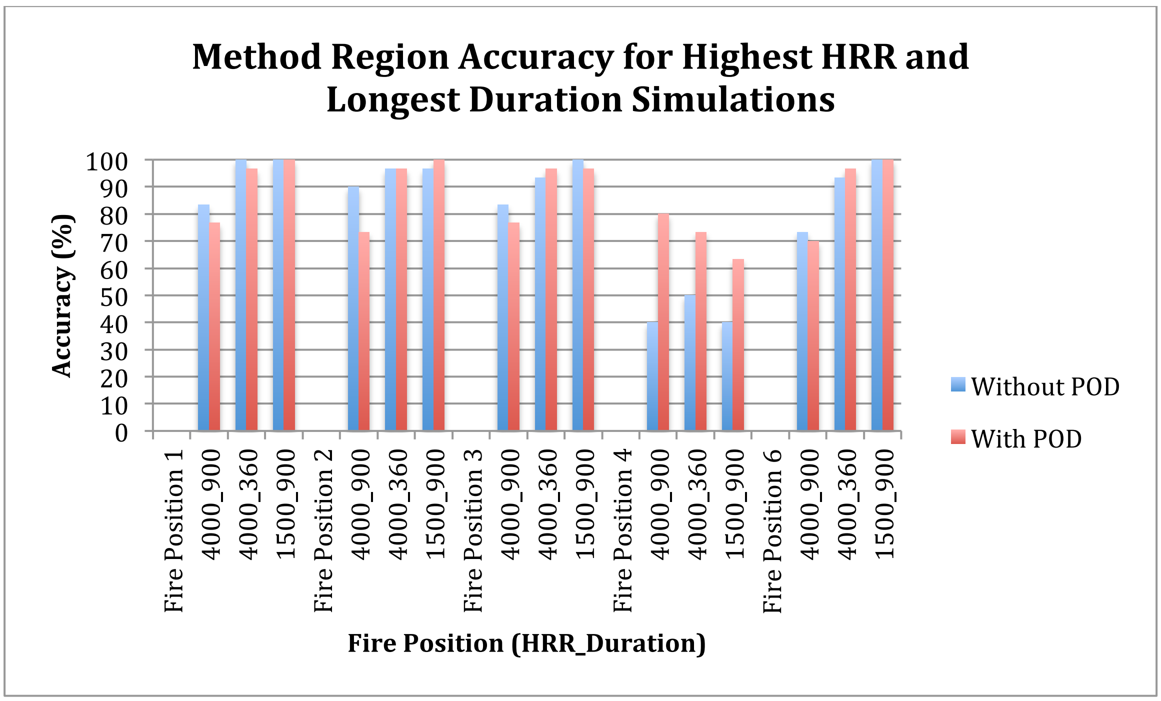


Figure G-85: Method Region Accuracy for the highest HRR and longest duration simulations

G.2.3 Center Point Accuracy Charts

There are two ways to evaluate accuracy using the X- and Y-coordinates of the center of the origin. The first validation test has already been reported above based on the calculation of the centroid for the answer sets with the POD and without the POD in comparison to the true center (Figures 22-53). This test clearly illustrated that 24 out of 32 (75%) of the scenarios where the POD was used resulted in a centroid closer to the true center (point of origin).

The second way to evaluate accuracy using the X- and Y-coordinates is to evaluate whether or not the participant coordinates fell within the prescribed area of origin. For each scenario, the participant's identified center of origin was considered accurate if it was contained in a circle with radius 45 pixels (diameter of 90) around the true origin center. A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 30 out of 32 scenarios (94%), a decrease in accuracy when using the POD in 0 out of 32 (0%), and no change in accuracy when using the POD in 2 out of 32 scenarios (6%) (Table G-8). It was found that 7 out of the 30 scenarios (23%) that were shown to increase in accuracy when using the POD were statistically significant (Table G-8). Overall there is a statistically significant increase in accuracy rates for the center point when the POD was used ($z=4.74$, $p<0.0001$) (Table G-8). The nonparametric Wilcoxon test is a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed.

Table G-8: Validation Results - Comparison of Center Point Accuracy Rates

Overall Comparison of Center Point Accuracy Rates without and with POD			
	Number of scenarios	**Total scenarios**	**%**
Increasing accuracy with the method	30	32	94
No change in accuracy	2	32	6
Decreasing accuracy with method	0	32	0
Statistical Significance Evaluation			
	# showing significant increase	**Total increasing scenarios**	**%**
Statistically significant increase (alpha=.05)	7	30	23
Test for Overall Significance			
	Without POD	**With POD**	
Mean (μ) accuracy rate	0.49	0.66	
Standard Deviation (σ)	0.11	0.11	
Median accuracy rates	0.50	0.66	
Independent samples t-test to compare means	t=6.00	p<0.0001	
Wilcoxon two-sample test to compare medians	z=4.74	p<0.0001	

To better evaluate any trends with the data, the center point accuracy was plotted for each fire position. The accuracy rates for this validity test were lower than those of previous validity studies, most likely due to the definition of accuracy being more difficult to achieve. The general trend was consistent with the other validity studies demonstrating a lower accuracy rates for the higher heat release rates and longer duration simulations (Figures G-86 through G-90). Again, fire position 4 had the lowest accuracy rates. Both of the physical experiments increased in accuracy with the use of the POD. The ATF study had a statistically significant increase ($p<0.001$) in accuracy when using the POD (Figure G-91).

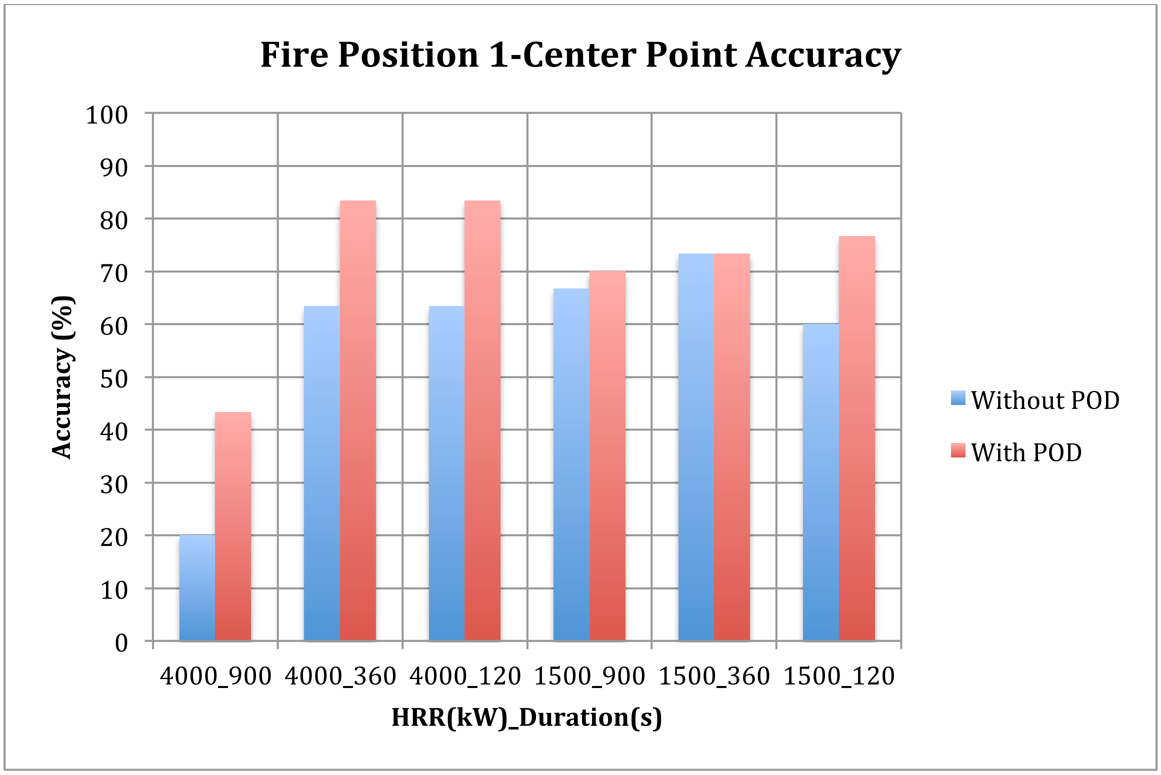


Figure G-86: Fire Position 1 Center Point Accuracy

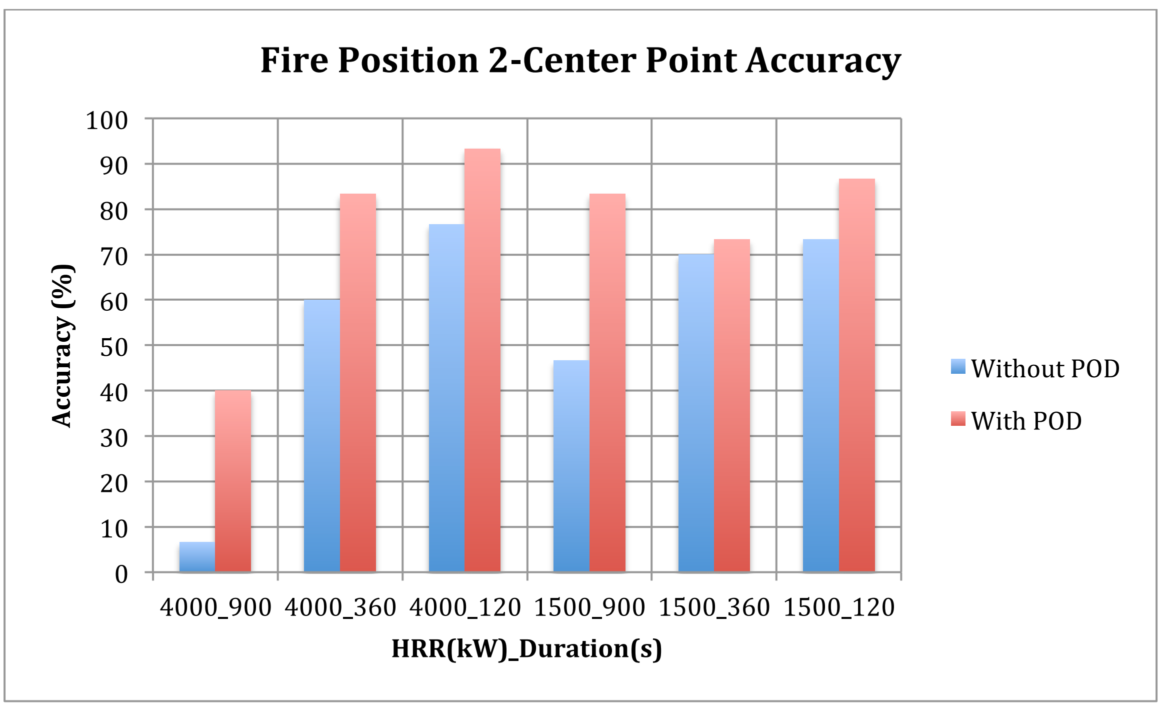


Figure G-87: Fire Position 2 Center Point Accuracy

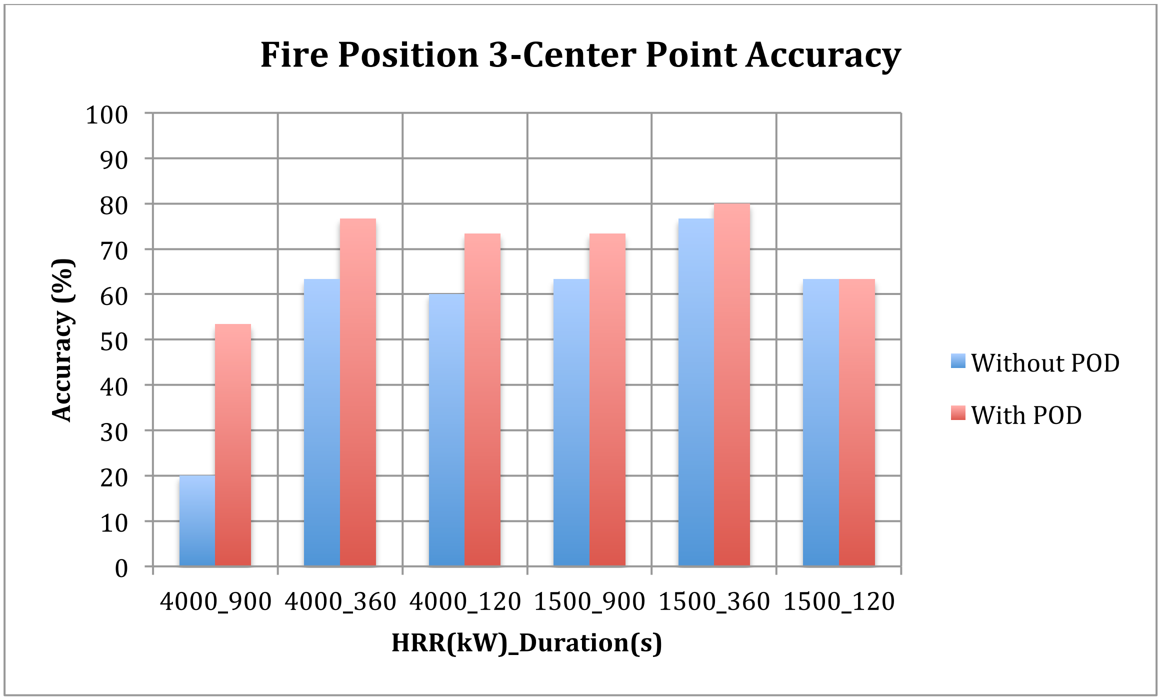


Figure G-88: Fire Position 3 Center Point Accuracy

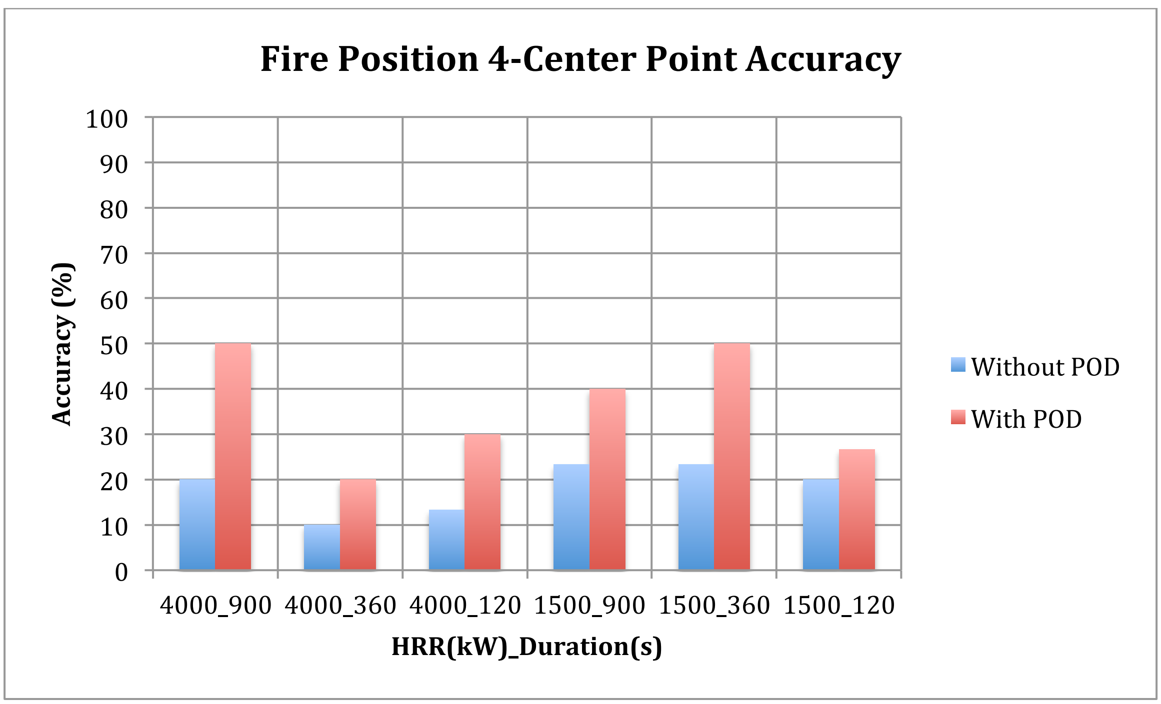


Figure G-89: Fire Position 4 Center Point Accuracy

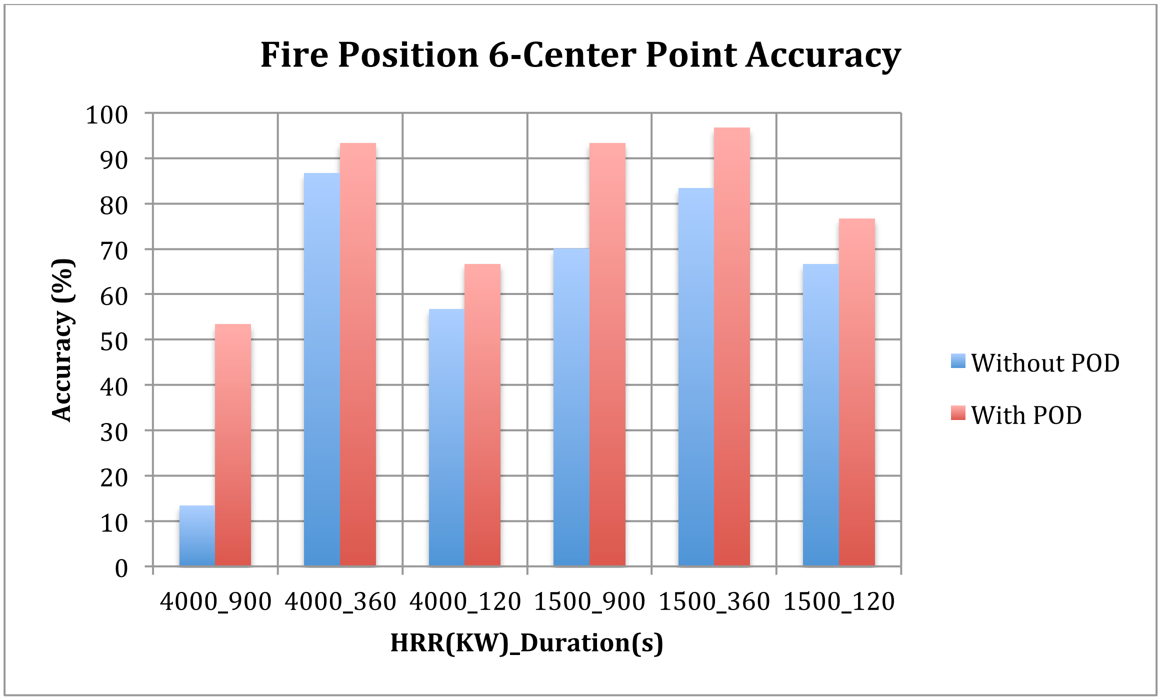


Figure G-90: Fire Position 6 Center Point Accuracy

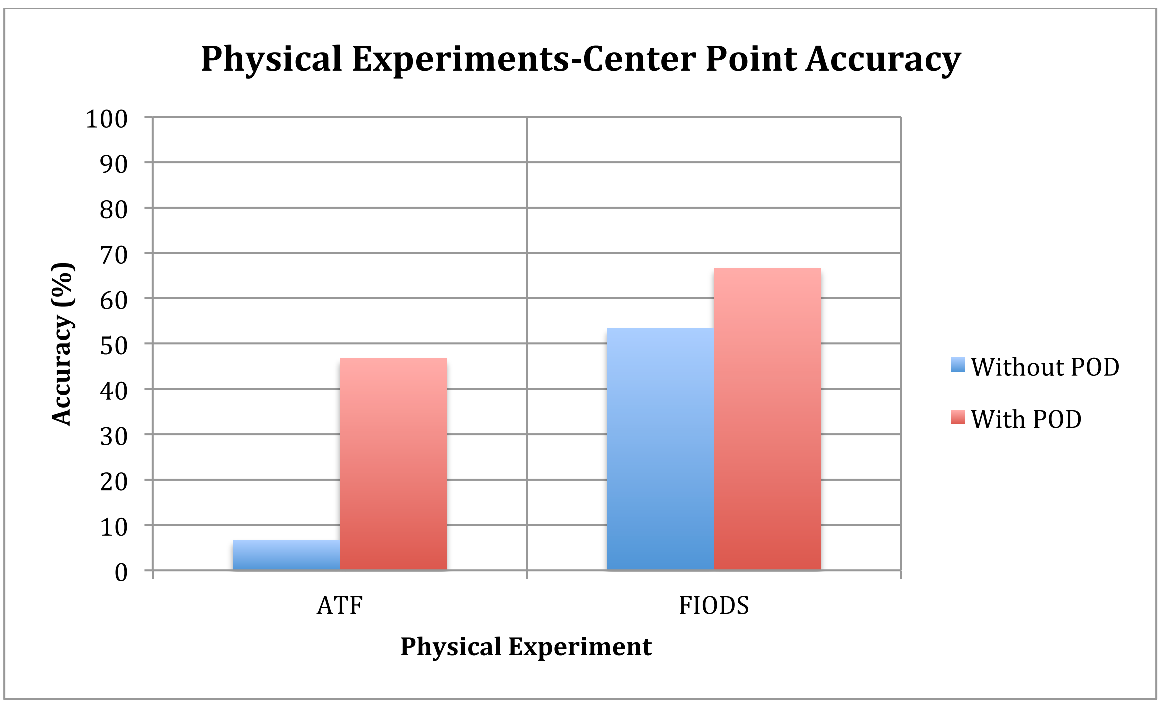


Figure G-91: Physical Experiments Center Point Accuracy

As the general trend indicated that the greatest variability was identified with the highest heat release rate and longest duration simulations, it was necessary to evaluate the results of these simulations more closely. The highest HRR and longest duration simulations were the 4000kW fires at 360 seconds and 900 seconds, and the 1500kW fire at 900 seconds. Specifically, it was important to evaluate the influence of the POD on these more difficult scenarios. Out of these simulations, all 15 performed better with the POD (100%) (Table G-9, Figure G-92).

Table G-9: Influence of the POD on the highest HRR and longest duration simulations

	Number of Scenarios	Total scenarios	%
Decreasing Accuracy w/POD	0	15	0
Increasing Accuracy w/POD	15	15	100
No Change in Accuracy	0	15	0

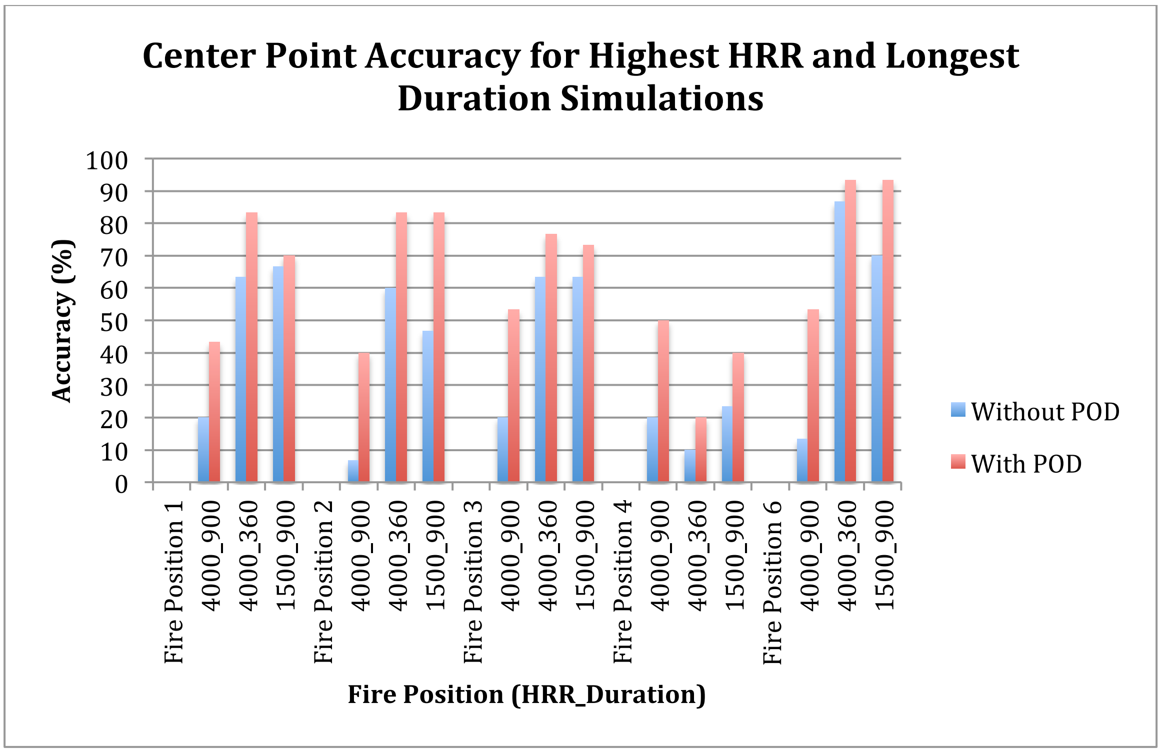


Figure G-92: Center Point Accuracy for the highest HRR and longest duration simulations

The distance between the centroid for the answer sets with the POD and without the POD were compared to the X- and Y-coordinate of the true origin. This test illustrated that 24 out of 32 (75%) of the scenarios where the POD was used resulted in a centroid closer to the true origin. The improvement in accuracy can be evaluated in terms of absolute distance as illustrated in figures G-93 and G-94. Using 11-cm then 22 out of the 32 scenarios reflected a meaningful change moving towards the true origin, while only 6 reflected a negative change.

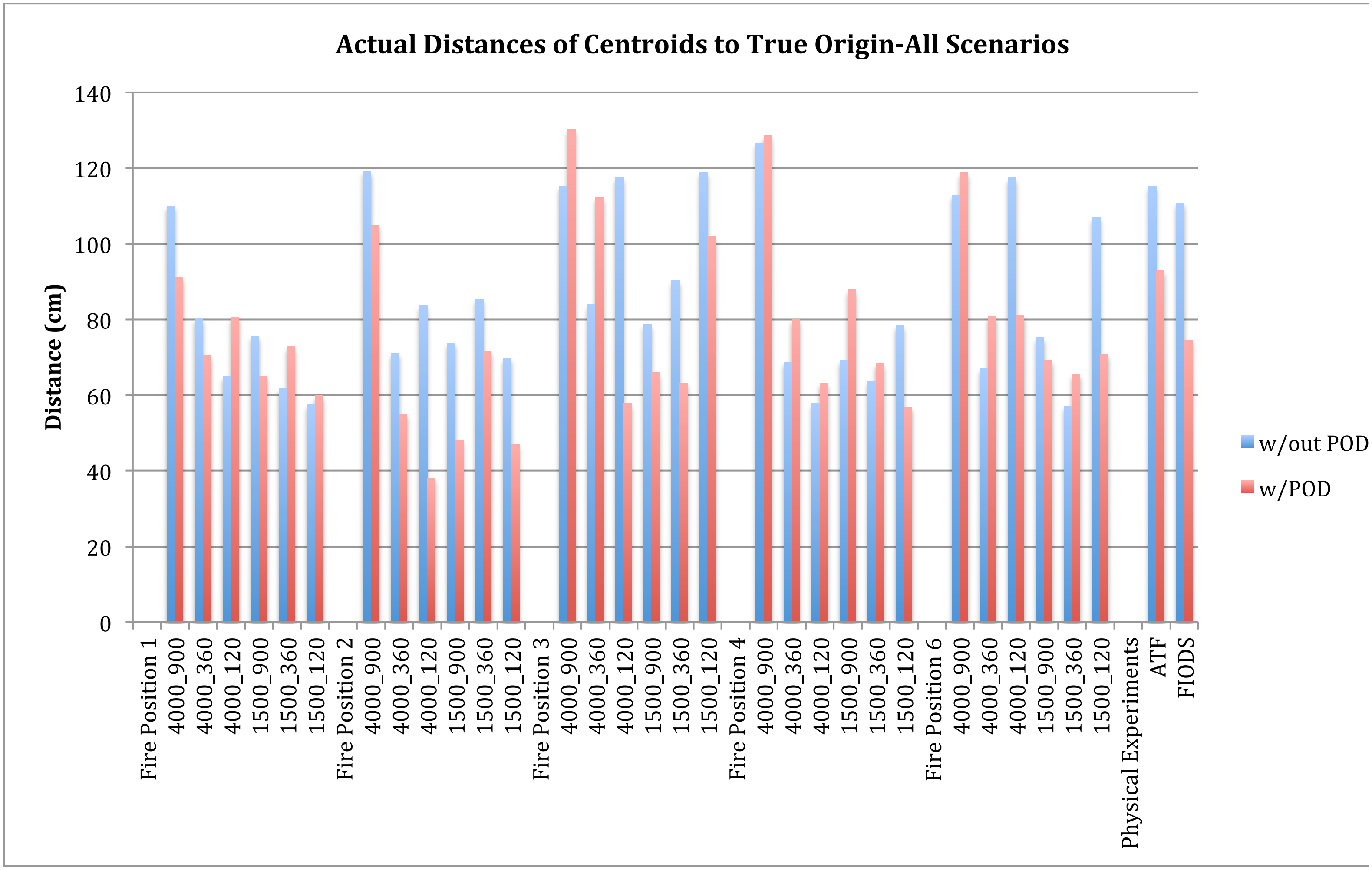


Fig G-93: Comparison of actual distance from centroid to true origin point without and with the POD

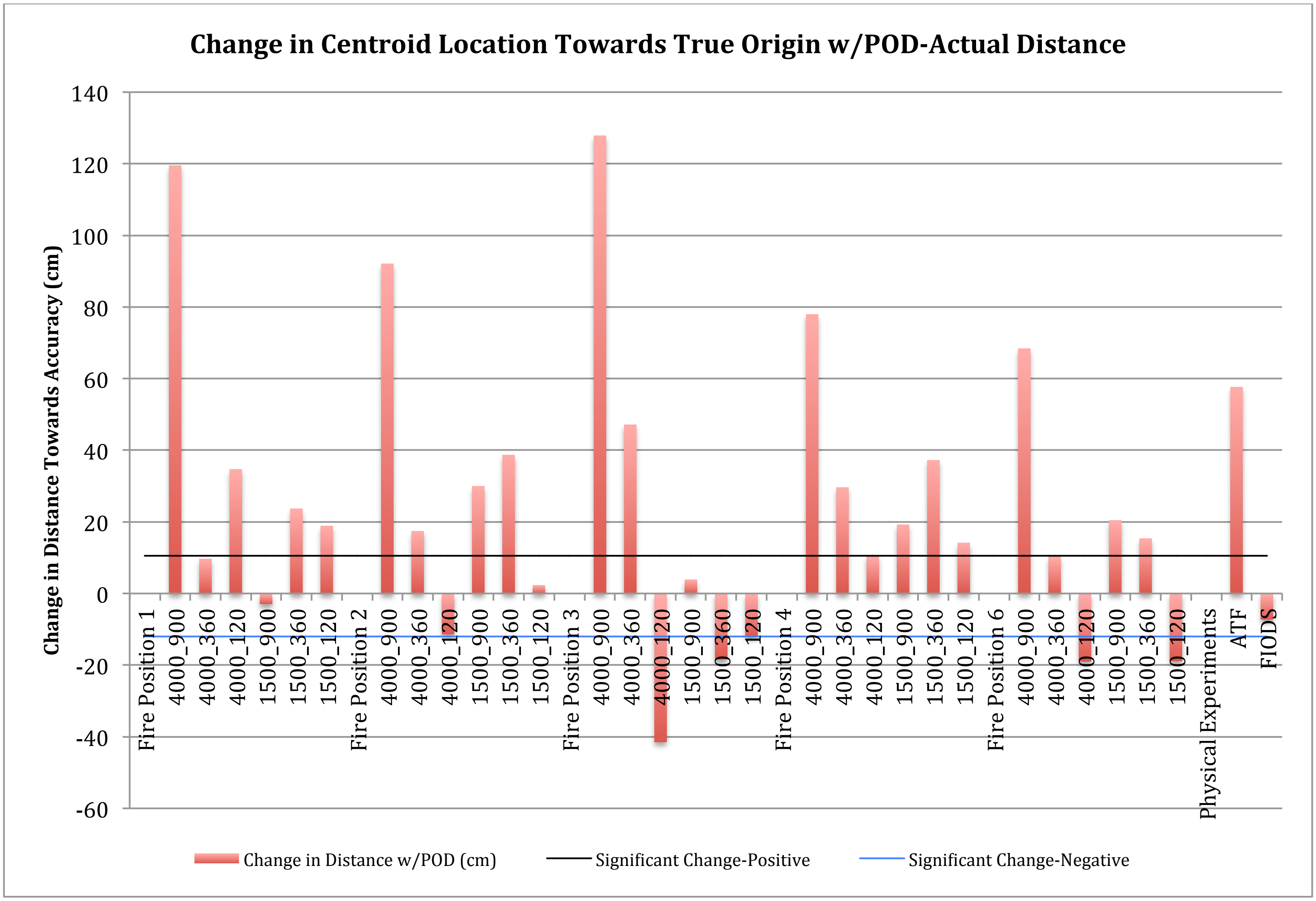


Fig G-94: Change of Distance Towards True Origin Point With Using POD (Significance Line added 11cm)

APPENDIX H – FDS Simulation and MATLAB Code

E.1 FDS Code

```
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&DUMP DT_BNDF=5.0, DT_DEVC=1.0, DT_DEVC_LINE=5./

&TIME T_END=1000.0 /

&REAC FUEL           = 'PROPANE'
    C              = 3
    H              = 8
    SOOT_YIELD       = 0.01
    CO_YIELD        = 0.02
    HEAT_OF_COMBUSTION = 46460. /

&SURF ID='FIRE', HRRPUA=1008.,RAMP_Q='fireramp', COLOR='RED' / 750 kW
&RAMP ID='fireramp', T=0, F=0.0 /
&RAMP ID='fireramp', T=16., F=0.01 /
&RAMP ID='fireramp', T=32., F=0.06 /
&RAMP ID='fireramp', T=48., F=0.14 /
&RAMP ID='fireramp', T=64., F=0.26 /
&RAMP ID='fireramp', T=80., F=0.40 /
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&RAMP ID='fireramp', T=920., F=0.65 /
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&RAMP ID='fireramp', T=1000., F=0.4 /

&MATL ID         = 'GYPSUM PLASTER'
    FYI         = 'Quintiere, Fire Behavior'
    CONDUCTIVITY  = 0.48
    SPECIFIC_HEAT = 0.84
    DENSITY      = 1440. /

&SURF ID          = 'WALL'
    DEFAULT      = .TRUE.
    RGB         = 200,200,200
    MATL_ID      = 'GYPSUM PLASTER'
    THICKNESS     = 0.016 /


FIRE LOCATIONS
&OBST XB= 1.52, 2.13, 1.61, 2.83, 0.00, 0.60, SURF_IDS='FIRE', 'INERT', 'INERT' / Propane Burner at location 1

OBST XB= 1.52, 2.13, 2.73, 3.95, 0.00, 0.60, SURF_IDS='FIRE', 'INERT', 'INERT'  Propane Burner at location 2
```

```
&OBST XB= 1.41, 5.27, 1.41, 1.51, 0.00, 2.44, SURF_ID='WALL' / Front wall *East
&HOLE XB= 4.11, 5.02, 1.41, 1.51, 0.00, 2.00 / Door
&OBST XB= 1.41, 1.51, 1.41, 5.27, 0.00, 2.44, SURF_ID='WALL' / Left wall *South
&OBST XB= 5.17, 5.27, 1.41, 5.27, 0.00, 2.44, SURF_ID='WALL' / Right wall *north
&OBST XB= 1.41, 5.27, 5.17, 5.27, 0.00, 2.44, SURF_ID='WALL' / Rear wall *West
&OBST XB= 1.41, 5.27, 1.41, 5.27, 2.44, 2.54, SURF_ID='WALL' / Ceiling

OBST XB= 1.52, 2.13, 1.61, 2.22, 0.00, 0.61, SURF_ID='WALL'  item 1
&OBST XB= 1.52, 2.13, 3.035, 3.645, 0.00, 0.61, SURF_ID='WALL' / item 2 -fire
&OBST XB= 1.52, 2.13, 4.46, 5.07, 0.00, 0.61, SURF_ID='WALL' / item 3
&OBST XB= 3.03, 3.64, 3.035, 3.645, 0.00, 0.61, SURF_ID='WALL' / item 4
&OBST XB= 3.2, 3.81, 1.52, 2.13, 0.00, 0.61, SURF_ID='WALL' / item 5
&OBST XB= 3.2, 3.81, 4.55, 5.16, 0.00, 0.61, SURF_ID='WALL' / item 6

&VENT MB='YMIN',SURF_ID='OPEN' /
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&VENT MB='XMIN', SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /
&VENT MB='ZMAX', SURF_ID='OPEN' /

&BNDF QUANTITY='GAUGE HEAT FLUX', STATISTICS='TIME INTEGRAL' /
&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='BURNING RATE' /
&SLCF PBX=4.57, QUANTITY='HRRPUV' / Heat Release Rate per Unit Volume
&SLCF PBX=4.57, QUANTITY='TEMPERATURE' /
&SLCF PBX=4.57, QUANTITY='HRRPUV' / Heat Release Rate per Unit Volume

&DEVC XYZ=3.34,3.34,2.1, QUANTITY='TEMPERATURE' / center of room
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&DEVC XYZ=3.34,3.34,0.3, QUANTITY='TEMPERATURE' /

&DEVC XYZ=4.57,5.1,2.1, QUANTITY='TEMPERATURE' /across from door
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&DEVC XYZ=4.57,5.1,0.3, QUANTITY='TEMPERATURE' /

&DEVC XYZ=4.57,1.51,2.1, QUANTITY='TEMPERATURE' / center of door
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&DEVC XYZ=4.0,3.34,0.0, QUANTITY='RADIATIVE HEAT FLUX', IOR=3 / center of room
&DEVC XYZ=4.57,1.51,0.0, QUANTITY='RADIATIVE HEAT FLUX', IOR=3 / center of door
&DEVC XYZ=4.57,5.1,0.0, QUANTITY='RADIATIVE HEAT FLUX', IOR=3 / across from door

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&DEVC XYZ=5.17, 1.6, 0.9, QUANTITY='GAUGE HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
```

LEFT SOUTH WALL

&DEVC XYZ=1.51, 1.6, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south wall DEVC25
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&DEVC XYZ=1.51, 1.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=1.51, 1.8, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south wall DEVC34
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&DEVC XYZ=1.51, 2.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.51, 2.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.51, 2.4, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south wall DEVC52
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&DEVC XYZ=1.51, 2.7, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south wall DEVC61
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&DEVC XYZ=1.51, 2.7, 0.9, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=1.51, 2.7, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.51, 3.0, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south wall DEVC70
&DEVC XYZ=1.51, 3.0, 2.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=1.51, 3.0, 1.2, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

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&DEVC XYZ=1.51, 3.3, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south
wall DEVC79
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&DEVC XYZ=1.51, 3.3, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.51, 3.6, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south
wall DEVC88
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&DEVC XYZ=1.51, 3.9, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south
wall DEVC97
&DEVC XYZ=1.51, 3.9, 2.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=1.51, 4.2, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south
wall DEVC106
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&DEVC XYZ=1.51, 4.5, 2.4, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / Left *south
wall DEVC115
&DEVC XYZ=1.51, 4.5, 2.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
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wall DEVC124
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wall DEVC133
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RIGHT NORTH WALL
&DEVC XYZ=5.17, 1.6, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north
wall DEVC142
&DEVC XYZ=5.17, 1.6, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=5.17, 1.8, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north
wall DEVC151
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&DEVC XYZ=5.17, 1.8, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
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wall DEVC160
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&DEVC XYZ=5.17, 2.1, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=5.17, 2.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 2.4, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north
wall DEVC169
&DEVC XYZ=5.17, 2.4, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 2.4, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 2.4, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=5.17, 2.4, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 2.7, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC178
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&DEVC XYZ=5.17, 2.7, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 3.0, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC187
&DEVC XYZ=5.17, 3.0, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.0, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
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&DEVC XYZ=5.17, 3.0, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.0, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.0, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.0, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.0, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 3.3, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC196
&DEVC XYZ=5.17, 3.3, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.3, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.3, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.3, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.3, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.3, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.3, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.3, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 3.6, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC205
&DEVC XYZ=5.17, 3.6, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.6, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.6, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.6, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.6, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.6, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.6, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 3.9, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC214
&DEVC XYZ=5.17, 3.9, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.9, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.9, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.9, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.9, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.9, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.9, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 3.9, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 4.2, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC223
&DEVC XYZ=5.17, 4.2, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.2, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.2, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.2, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.2, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.2, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.2, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.2, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 4.5, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC232
&DEVC XYZ=5.17, 4.5, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.5, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.5, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.5, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.5, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.5, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.5, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.5, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 4.8, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC241
&DEVC XYZ=5.17, 4.8, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.8, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.8, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.8, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.8, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.8, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.8, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 4.8, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.17, 5.1, 2.4, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / Right *north wall DEVC250
&DEVC XYZ=5.17, 5.1, 2.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 5.1, 1.8, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 5.1, 1.5, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 5.1, 1.2, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 5.1, 0.9, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 5.1, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 5.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=5.17, 5.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

FRONT EAST WALL
&DEVC XYZ=1.6, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC259
&DEVC XYZ=1.6, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.8, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC268
&DEVC XYZ=1.8, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.8, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.8, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.8, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.8, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.8, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.8, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.8, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=2.1, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC277
&DEVC XYZ=2.1, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=2.4, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC286
&DEVC XYZ=2.4, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.4, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.4, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.4, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.4, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.4, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.4, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.4, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=2.7, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC295
&DEVC XYZ=2.7, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.7, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.7, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.7, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.7, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.7, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.7, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.7, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.0, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC304
&DEVC XYZ=3.0, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.0, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.0, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.0, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.0, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.0, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.0, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.0, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.3, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC313
&DEVC XYZ=3.3, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.6, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC322
&DEVC XYZ=3.6, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.9, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC331
&DEVC XYZ=3.9, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.9, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.9, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.9, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.9, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.9, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.9, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.9, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=4.2, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC340
&DEVC XYZ=4.2, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.2, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.2, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.2, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.2, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.2, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.2, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.2, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=4.5, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC349
&DEVC XYZ=4.5, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.5, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.5, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.5, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.5, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.5, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.5, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.5, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=4.8, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC358
&DEVC XYZ=4.8, 1.51, 2.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.8, 1.51, 1.8, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.8, 1.51, 1.5, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.8, 1.51, 1.2, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.8, 1.51, 0.9, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.8, 1.51, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.8, 1.51, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=4.8, 1.51, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=5.1, 1.51, 2.4, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / Front *east wall DEVC367
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REAR WEST WALL
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wall DEVC421
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wallDEVC430
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wall DEVC439
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wall DEVC448
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wall DEVC457
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wall DEVC466
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wall DEVC475
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wall DEVC484
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CEILING
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left face-none

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&DEVC XYZ=2.1, 3.645, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
CONTENT ITEM 3 OBST XB= 1.52, 2.13, 4.46, 5.07, 0.00, 0.61, SURF_ID='WALL'
&DEVC XYZ=1.6, 4.46, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=1.6, 4.46, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 4.46, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.9, 4.46, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=1.9, 4.46, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.9, 4.46, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=2.1, 4.46, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=2.1, 4.46, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 4.46, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

left face-none

&DEVC XYZ=2.13, 4.5, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=2.13, 4.5, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

```
&DEVC XYZ=2.13, 4.5, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=2.13, 4.8, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=2.13, 4.8, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.13, 4.8, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=2.13, 5.0, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=2.13, 5.0, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.13, 5.0, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.6, 5.07, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=1.6, 5.07, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.6, 5.07, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=1.9, 5.07, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=1.9, 5.07, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=1.9, 5.07, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=2.1, 5.07, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=2.1, 5.07, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=2.1, 5.07, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

CONTENT ITEM 4 OBST XB= 3.03, 3.64, 3.035, 3.645, 0.00, 0.61, SURF_ID='WALL'
&DEVC XYZ=3.1, 3.035, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=3.1, 3.035, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.1, 3.035, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /


&DEVC XYZ=3.4, 3.035, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=3.4, 3.035, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.4, 3.035, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.6, 3.035, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=3.6, 3.035, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 3.035, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.03, 3.1, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.03, 3.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.03, 3.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /


&DEVC XYZ=3.03, 3.4, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.03, 3.4, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.03, 3.4, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.03, 3.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.03, 3.6, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.03, 3.6, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.64, 3.1, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.64, 3.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.64, 3.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.64, 3.4, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.64, 3.4, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.64, 3.4, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.64, 3.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.64, 3.6, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.64, 3.6, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
```

&DEVC XYZ=3.1, 3.645, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=3.1, 3.645, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.1, 3.645, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.4, 3.645, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=3.4, 3.645, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.4, 3.645, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.6, 3.645, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=3.6, 3.645, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 3.645, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

CONTENT ITEM 5 OBST XB= 3.2, 3.81, 1.52, 2.13, 0.00, 0.61, SURF_ID='WALL'
front face - none
&DEVC XYZ=3.2, 1.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.2, 1.6, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.2, 1.6, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.2, 1.9, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.2, 1.9, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.2, 1.9, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.2, 2.1, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.2, 2.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.2, 2.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.81, 1.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.81, 1.6, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.81, 1.6, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.81, 1.9, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.81, 1.9, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.81, 1.9, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.81, 2.1, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.81, 2.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.81, 2.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.3, 2.13, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=3.3, 2.13, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 2.13, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.6, 2.13, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=3.6, 2.13, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 2.13, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.8, 2.13, 0.6, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' / rear face
&DEVC XYZ=3.8, 2.13, 0.3, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.8, 2.13, 0.1, QUANTITY='NET HEAT FLUX', IOR=2, STATISTICS='TIME INTEGRAL' /

CONTENT ITEM 6 OBST XB= 3.2, 3.81, 4.55, 5.16, 0.00, 0.61, SURF_ID='WALL'
&DEVC XYZ=3.3, 4.55, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=3.3, 4.55, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.3, 4.55, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.6, 4.55, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=3.6, 4.55, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.6, 4.55, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.8, 4.55, 0.6, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' / front face
&DEVC XYZ=3.8, 4.55, 0.3, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

```
&DEVC XYZ=3.8, 4.55, 0.1, QUANTITY='NET HEAT FLUX', IOR=-2, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.2, 4.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.2, 4.6, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.2, 4.6, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.2, 4.9, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.2, 4.9, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.2, 4.9, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.2, 5.1, 0.6, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' / left face
&DEVC XYZ=3.2, 5.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.2, 5.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=-1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.81, 4.6, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.81, 4.6, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.81, 4.6, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.81, 4.9, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.81, 4.9, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.81, 4.9, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /

&DEVC XYZ=3.81, 5.1, 0.6, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' / right face
&DEVC XYZ=3.81, 5.1, 0.3, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
&DEVC XYZ=3.81, 5.1, 0.1, QUANTITY='NET HEAT FLUX', IOR=1, STATISTICS='TIME INTEGRAL' /
rear face - none

&TAIL /
```

E.2 MATLAB Code

```
clear all
clc
close all

%% Import the data
% [~, ~, raw] = xlsread('/Users/greggorbett/Desktop/Definitional
Paper/FDS
Simulations/35/dissertation35_devc.csv','dissertation35_devc.csv');
% raw = raw(3:end,:);
%
% %% Replace non-numeric cells with 0.0
% R = cellfun(@(x) ~isnumeric(x) || isnan(x),raw); % Find non-numeric
cells
% raw(R) = {0.0}; % Replace non-numeric cells
%
% %% Create output variable
% untitled = cell2mat(raw);
%
% %% Clear temporary variables
% clearvars raw R;

fileToRead1= ('/Users/greggorbett/Desktop/Definitional Paper/FDS
Simulations/35/dissertation35_devc.csv');

newData1 = importdata(fileToRead1);

% Create new variables in the base workspace from those fields.
vars = fieldnames(newData1);
for i = 1:length(vars)
    assignin('base', vars{i}, newData1.(vars{i}));
end

% data = untitled;
time_row=[63, 123, 183, 243, 303, 363, 423, 483, 543, 603, 663, 723,
783, 843, 903, 963, 1003];
% time_row=[63];



for ct_1 = 1:1:length(time_row);
    z = time_row(ct_1)-3; % subract 3 because the headers of excel file
were removed during data import
    data_z = data(z,:)';

    %South Wall
    ct_2=1;
    for del_1=28:9:144;

South_wall(1:9,ct_2,ct_1)=data_z(del_1:del_1+8)./1000;%converting kJ to
MJ
        ct_2=ct_2+1;
    end
```

```
    %North Wall
    ct_2=1;
    for del_1=145:9:261;
        North_wall(1:9,ct_2,ct_1)=data_z(del_1:del_1+8)./1000;
        ct_2=ct_2+1;
    end

    %East Wall
    ct_2=1;
    for del_1=262:9:378;
        East_wall(1:9,ct_2,ct_1)=data_z(del_1:del_1+8)./1000;
        ct_2=ct_2+1;
    end

    %West Wall
    ct_2=1;
    for del_1=379:9:495;
        West_wall(1:9,ct_2,ct_1)=data_z(del_1:del_1+8)./1000;
        ct_2=ct_2+1;
    end

    %ceiling
    ct_2=1;
    for del_1=496:13:664;
        Ceiling(1:13,ct_2,ct_1)=data_z(del_1:del_1+12)./1000;
        ct_2=ct_2+1;
    end

end


% figure('Units','normalized','Position',[0.15 0.15 0.70 0.65])
% colormap(flipud(gray))
% contourf(South_wall(:,:,1),'DisplayName','data');figure(gcf),
set(gca,'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13])
% colorbar
% % caxis([6, 14])
% axis ij
% grid on, xlabel('Vertical measurement point'), ylabel('Horizontal
measurement point')
% title('Depth of Calcination South wall')




%
% for ct_3=1:1:length(time_row);
%
% figure;
% contour(South_wall(:,:,ct_3))
%
% figure
% contour(North_wall(:,:,ct_3))
%
% figure
% contour(East_wall(:,:,ct_3))
%
```

```
% figure
% contour(West_wall(:,:,ct_3))
%
% figure
% contour(Ceiling(:,:,ct_3))
% end


for ct_3=1:1:length(time_row);

figure('Units','normalized','Position',[0.15 0.15 0.70 0.65])
colormap(flipud(gray))
contourf(South_wall(:,:,ct_3),'DisplayName','data');figure(gcf),
set(gca,'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13])
colorbar
caxis([0, 20])
axis ij
grid on, xlabel('Vertical measurement point'), ylabel('Horizontal
measurement point')
title('South wall-Time Integral Net Heat Flux')


% figure('Units','normalized','Position',[0.15 0.15 0.70 0.65])
% colormap(flipud(gray))
% contourf(North_wall(:,:,ct_3),'DisplayName','data');figure(gcf),
set(gca,'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13])
% colorbar
% caxis([0, 20])
% axis ij
% grid on, xlabel('Vertical measurement point'), ylabel('Horizontal
measurement point')
% title('North wall-Time Integral Net Heat Flux')

% figure('Units','normalized','Position',[0.15 0.15 0.70 0.65])
% colormap(flipud(gray))
% contourf(East_wall(:,:,ct_3),'DisplayName','data');figure(gcf),
set(gca,'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13])
% colorbar
% caxis([0, 20])
% axis ij
% set(gca, 'xdir', 'reverse')
% grid on, xlabel('Vertical measurement point'), ylabel('Horizontal
measurement point')
% title('East wall-Time Integral Net Heat Flux')

% figure('Units','normalized','Position',[0.15 0.15 0.70 0.65])
% colormap(flipud(gray))
% contourf(West_wall(:,:,ct_3),'DisplayName','data');figure(gcf),
set(gca,'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13])
% colorbar
% caxis([0, 20])
% axis ij
% grid on, xlabel('Vertical measurement point'), ylabel('Horizontal
measurement point')
% title('West wall-Time Integral Net Heat Flux')

% figure('Units','normalized','Position',[0.15 0.15 0.70 0.65])
```

```
% colormap(flipud(gray))
% contourf(Ceiling(:,:,ct_3),'DisplayName','data');figure(gcf),
set(gca,'XTick',[1 2 3 4 5 6 7 8 9 10 11 12 13])
% colorbar
% caxis([0, 20])
% axis ij
% grid on, xlabel('Vertical measurement point'), ylabel('Horizontal
measurement point')
% title('Ceiling-Time Integral Net Heat Flux')


end
```

APPENDIX I – Survey

The four surveys are provided in the following order:
(1)-No POD with contents
(2)-POD with contents
(3)-No POD without contents
(4)-POD without contents